One-step induction of human GABAergic neurons promotes presynaptic development & synapse maturation

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Abstract (174 words)

Human induced pluripotent stem cells (iPSCs) present a powerful approach to study human brain physiology and disease, yet robust, pure GABAergic induction has remained difficult. Here we present improved, single-step, transposon-based GABAergic induction with Ascl1/Dlx2, which yields pure GABAergic neurons, in contrast to lentiviral approaches, and was tested across three independent iPSC lines. Proteomic and electrophysiological characterization at different developmental time points showed that these neurons gain a proteomic profile that maps to different cortical interneuron subtypes, particularly VIP+ interneurons, and display typical GABAergic synaptic properties, producing large, synchronous and picrotoxin-sensitive currents. During early development synaptic strength increased threefold, which was accompanied by enhanced expression of multiple GABA-specific presynaptic gene sets, but few changes in postsynaptic gene sets. Synaptic strength continued to improve during late development but with only minor proteomic changes. Co-

seeding with NGN2 neurons created stable networks of predefined excitation/inhibition ratios, with corresponding synapse ratios. Taken together, transposon-based GABAergic induction yields pure, mature GABAergic neurons suitable for studying gene sets involved in synaptic maturation and to build excitation/inhibition networks for disease modelling.

Keywords (max 10)

Induced pluripotent stem cells, induced GABAergic neurons, Transposon, Synaptic maturation, Ascl1, Dlx2, Autaptic neurons, Proteomics, Patch-clamp, Excitation/inhibition

Introduction

Human induced pluripotent stem cell (iPSC)-derived models provide a promising platform for studying human brain physiology and pathology. iPSCs can be generated from patient-derived tissue or blood to better reflect the human genetics and (patho)physiology compared to commonly employed rodent models (Breschi *et al*, 2017; Gharib & Robinson-Rechavi, 2011; Hoffman *et al*, 2019). GABAergic dysfunction and excitation/inhibition (E/I) disbalance have been implicated in many neurodevelopmental and neurodegenerative disorders (Busche *et al*, 2008; Foss-Feig *et al*, 2017; Nelson & Valakh, 2015; Palop *et al*, 2007a; Rubenstein & Merzenich, 2003; Sohal & Rubenstein, 2019). In recent years, various strategies have been developed for generating iPSC-derived GABAergic neurons, but robust, pure GABAergic induction remains challenging. Directed differentiation, which employs signalling molecules to mimic neurodevelopment(Liu *et al*, 2013; Maroof *et al*, 2013; Nicholas *et al*, 2013), yields both glutamatergic and GABAergic neurons, but these type of inductions often generate inconsistent E/I ratios, tend to yield heterogeneous and immature neuronal populations and are costly and time-consuming(Engle *et al*, 2018). Rapid differentiation approaches rely on overexpression of key transcription factors, such as Ascl1 and Dlx2 for GABAergic differentiation,(Mossink *et al*, 2022; Yang *et al*, 2017b) and often rely on lentiviral delivery of transgenes. However, such approaches have several limitations: (1) they require multiple vectors when delivering multiple transgenes due to the size cap of ~8 kb, (2) they pose a risk of disrupting host genes(Baum, 2007), and (3) they are susceptible to epigenetic silencing during prolonged iPSC culturing (Cabrera *et al*, 2022; Wolf & Goff, 2009; Yao *et al*, 2004). To overcome these challenges, TALEN- and CRISPR-based gene editing(Miller *et al*, 2011) have been used to target the transgenes to the *AAVS1* safe harbour locus(Peitz *et al*, 2020; Schmid *et al*, 2021). While this ensures stable transgene expression, allows for delivery of multiple genes in a single construct, and minimizes off-target effects,

it is time and resource-consuming due to the need for clonal expansion and extensive validation of every iPSC line used in a study(Lombardo *et al*, 2011).

The PiggyBac transposon system has emerged as a gene-delivery tool that overcomes most of these limitations. Unlike lentiviral systems, transposons enable stable genomic integration of large genetic constructs up to 200 kb(Li *et al*, 2013) through a "cut-and-paste" mechanism(Wilber *et al*, 2007), which enables delivery of multiple transgenes in a single construct. Additionally, transposon-delivered transgenes are less prone to silencing than lentivirally delivered transgenes(Ng *et al*, 2021) and the increased packing capacity permits the inclusion of epigenetic regulators to further diminish silencing. Compared to safe-harbour insertion of transgenes, the delivery of a transposon cassette is a simpler, single-step process applicable to multiple iPSC lines in parallel and allows the use of a polyclonal population for most use cases, eliminating the need for thorough validation, thereby accelerating experimental timelines.

Here, we characterize PiggyBac transposon-based overexpression of *Ascl1* and *Dlx*2 (PB-AD) for GABAergic neuronal induction and benchmark this against established GABAergic induction methods. PB-AD-based induction results in pure GABAergic differentiation across different genetic backgrounds, with proteomic signatures characteristic of several human cortical interneuron types, with the strongest resemblance to VIP^+ interneurons, unlike lentiviral-based AD expression, which induces both GABAergic and glutamatergic differentiation. We demonstrate that PB-AD neurons integrate into synaptically connected E/I networks when co-cultured with excitatory NGN2 neurons with synaptic projections proportional to cellular ratios. Using proteomics, patch-clamp electrophysiology, and immunocytochemistry we show that functional synapse maturation correlates with increasing levels of proteins in presynaptic gene sets, resulting in reliable, plastic synapses that synchronously release GABA, whereas postsynaptic function and protein composition are stable over time. We propose that this improved GABAergic induction protocol, which reliably generates pure GABAergic neurons, enables the study of human GABAergic functioning in pure GABAergic networks, in single-neuron (autaptic) cultures, and stable E/I-networks.

Results

GABAergic differentiation of human iPSCs using PiggyBac based delivery of Ascl1 and Dlx2

Overexpression of the transcription factors Ascl1 and Dlx2 drives GABAergic lineage specification of induced pluripotent stem cells (iPSCs)(Yang *et al*, 2017a). Previous approaches

103 employed separate lentivectors to express both genes in an inducible manner. We aimed to
104 develop a simplified GABAergic differentiation protocol using a single PiggyBac transposon
105 construct containing both transcription factors (Figure 1A). This vector contains (1) a
106 doxycycline (dox)-inducible expression cassette for *Ascl1* and *Dlx2* from a bidirectional
107 promoter, avoiding variation in expression levels resulting from position effects in multi-
108 cistronic vectors; (2) reverse tetracycline-controlled transactivator (rtTA), required for dox-
109 inducible expression; (3) the puromycin resistance gene (pac), allowing for antibiotic
110 selection, as well as (4) mTagBFP2(Subach *et al*, 2011), giving transfected cells a fluorescent
111 marker; and (5) Ubiquitous Chromatin Opening Elements (UCOE)(Müller-Kuller *et al*, 2015)
112 and 5'HS chicken β-globin (cHS4) insulator elements(Chung *et al*, 1997). Firstly, we tested
113 whether our newly designed construct could induce GABAergic differentiation (Figure 1B). To
114 this end, we co-transfected this PiggyBac vector with a transposase vector into BIONi010-C
115 iPSCs(Rasmussen *et al*, 2014). After puromycin-selection, all cells expressed mTagBFP2
116 (Figure 1C), confirming successful transgene integration. Upon dox-induction, cells first
117 clustered together (Figure 1D) and after releasing and reseeding at 3 days post-induction
118 (DPI), cells developed a neuronal morphology, which became more distinct within one week
119 (Figure 1E). At 10 weeks post-induction (WPI), neurons displayed MAP2+ dendrites and $VGAT^+$
120 puncta, indicative of GABAergic synapses, whereas glutamatergic $VGLUT1/2^+$ puncta were
121 absent (Figure 1F,G).

122 *GABAergic synaptic transmission in PiggyBac Ascl1/Dlx2 neurons*

123 To confirm the GABAergic identity of PiggyBac-induced neurons we performed voltage-clamp
124 recordings in autaptic cultures(Js *et al*, 2019) between 6 and 10 WPI (Figure 1H). Rapid
125 depolarization to +30 mV induced action potential evoked postsynaptic currents (ePSCs),
126 which displayed slow decay times (τ) characteristic of GABAergic currents(Jones & Westbrook,
127 1995), as determined by mono-exponential fits (geometric mean (GM) = 104.2 ms, geometric
128 SD factor (GM_{SDf}) = 1.42; Figure 1I,J). Furthermore, virtually all synaptic signalling was
129 abolished after applying the GABA receptor antagonist picrotoxin (PTX), confirming
130 GABAergic synaptic identity (Figure 1I,K).

131 *PiggyBac Ascl1/Dlx2 yields a pure GABAergic neuron population in contrast to lentiviral methods*

132 To benchmark the PiggyBac approach, we compared it with two established lentiviral
133 methods for GABAergic induction(Mossink *et al.*, 2022; Yang *et al.*, 2017a) and an NGN2-based
134 protocol for glutamatergic induction(Meijer *et al*, 2019; Schmid *et al.*, 2021) (Figure 1L).
135 Autaptic neurons were generated using all four protocols and ePSC decay time constants
136 were quantified using mono-exponential fits. As expected, NGN2-derived neurons exhibited

137 fast ePSCs decay kinetics typical of glutamatergic transmission (GM = 2.43 ms, GM_{SDf} = 1.39,
138 Figure 1M,N), confirmed pharmacologically and by the presence of VGLUT1/2$^+$ puncta (Figure
139 S1). Surprisingly, decay time constants from neurons generated with the lentiviral GABAergic
140 protocols showed a bimodal distribution which could be fitted with a sum of two gaussians.
141 More than half of the cells in these cultures exhibited ePSC kinetics comparable to those in
142 the NGN2 cultures (Lenti AF: GM = 2.82 ms, GM_{SDf} = 0.58, 72.8% of the fit; Lenti AD: GM = 4.62
143 ms, GM_{SDf} = 0.42, 55.3% of the fit). The remaining cells had more than tenfold larger time
144 constants typical for slow GABAergic ePSCs (Lenti AF: GM = 86.3 ms, GM_{SDf} = 1.56 for 27,2%
145 of the fit; Lenti AD: GM = 60.5 ms, GM_{SDf} = 1.26 for 44.7% of the fit). In contrast, the PB-AD
146 method produced a unimodal population with slowly decaying ePSCs (GM = 78.9 ms, GM_{SDf}
147 = 1.35). Since NGN2 and PB-AD neurons produced decay time constants with unimodal fits,
148 these values were used to determine cut-off thresholds for synaptic identity (glutamatergic:
149 $\tau \leqslant 6$ ms; GABAergic: $\tau \geqslant 30$ ms; mixed: $6 < \tau < 30$ ms). This revealed that 68% of PB-AD
150 neurons exhibited GABAergic currents, while the remaining 32% were synaptically silent
151 (Figure 1O). In contrast, the lentiviral approaches generated a substantial population of
152 glutamatergic (Lenti AF: 43%, Lenti AD: 39%) and mixed (Lenti AF: 9% Lenti AD: 15%)
153 identities. The consistent generation of functional GABAergic neurons and the absence of
154 glutamatergic neurotransmission underscore the reliability of the PB-AD protocol compared
155 to previously described methods.

156 *PiggyBac Ascl1/Dlx2 protocol induces GABAergic neurons across genetic backgrounds*
157 To test for generalizability, we applied the PB-AD protocol to generate neurons from two
158 additional iPSC lines, KOLF2.1J(Pantazis *et al*, 2022) and GM23973(Nadadhur *et al*, 2019), and
159 characterized their functional properties at 7 and 6 WPI, respectively. In both lines the PB-
160 AD approach produced neurons with GABAergic synaptic projections and slow-decaying
161 synaptic transmission, indicative of GABAergic specification (Figure S2), as was found for the
162 BIONi010-C line. These findings demonstrate the protocol's applicability across genetic
163 backgrounds.

164 *PiggyBac Ascl1/Dlx2 neurons integrate into controlled excitatory/inhibitory networks*
165 To test whether PB-AD neurons integrate into E/I networks alongside glutamatergic neurons,
166 we co-cultured 3 DPI PB-AD neurons with 3 DPI glutamatergic NGN2 neurons in networks
167 containing 100%, 30% (as found in the human cortex(Bakken *et al*, 2021; Fang *et al*, 2022;
168 Loomba *et al*, 2022)) and 0% inhibitory neurons (Figure 2A-C). Immunocytochemistry at 10
169 WPI (Figure 2B,C) revealed comparable neuronal cell densities across all conditions, as
170 measured by NeuN staining, indicating similar viability of PB-AD and NGN2 neurons. (Figure

171 2D). Total dendrite length per field of view increased as the proportion of PB-AD neurons
172 decreased, consistent with the distinct morphological characteristics of GABAergic
173 neurons(Chang *et al*, 2014) (Figure 2E). Pure PB-AD networks contained VGAT$^+$ (GABAergic)
174 synaptic puncta, and NGN2 networks contained VGLUT1/2$^+$ (glutamatergic) synaptic puncta,
175 with in both cases virtually no puncta of the other type present (Figure 2F,G). In contrast, the
176 mixed (30% PB-AD) networks contained both GABAergic and glutamatergic puncta on the
177 same dendrite proportional to cellular ratios, demonstrating that PB-AD neurons are viable
178 components for assembling E/I networks when mixed with NGN2 neurons.

179 *PiggyBac Ascl1/Dlx2 neurons acquire a GABAergic molecular identity over time*

180 Next, we assessed differentiation of PB-AD and NGN2 neurons over time using mass
181 spectrometry-based proteomics. PB-AD co-cultures with rat astrocytes were compared to
182 NGN2 co-cultures at 4, 6, 8, and 10 WPI (Figure 3A). We detected 99,154 human peptide
183 precursors mapping to 7,775 unique proteins across 60 samples that passed quality control.
184 Variability within groups was low-to-moderate with coefficients of variation between 14.6%
185 and 32.2%, reflecting consistent detection across replicates (Figure S3A-B). To remove rat
186 astrocytic signal, subsequent analyses focused on neuronally enriched proteins (1690
187 proteins). Principal component analysis (PCA) on the neuronally-enriched protein
188 abundances (Figure 3B, S3C) revealed clear separation between PB-AD and NGN2 cultures
189 along the first two components (PC1: 71.5% and PC2: 6.1%), as well as the separation of
190 different time points within each culture. More specifically, time points from both PB-AD and
191 NGN2 cultures showed clear separation between 4, 6, and 8 WPI, while cultures at 8 and 10
192 WPI clustered more closely together, suggesting that proteomic maturation plateaus after 8
193 weeks.

194 To assess lineage specification of PB-AD and NGN2 inductions, we annotated cell
195 types based on differentially expressed proteins using cell type specificity scores (CTSS),
196 computed using single-cell RNA expression data from human cortex(Jorstad *et al*, 2023)
197 (Figure S4A). Across all timepoints, canonical GABAergic proteins, including SLC32A1 (VGAT),
198 GAD1, GAD2, were enriched in PB-AD cultures. In addition, other predicted GABAergic
199 proteins, such as CRHBP, FBN2, CRH, and RELN, were enriched in PB-AD neurons. In contrast,
200 only a few predicted glutamatergic proteins (e.g., BDNF, PCP4, CPZ, and ADAMTSL1) were
201 moderately enriched in PB-AD cultures. The glutamatergic marker SLC17A6 (VGLUT2) was
202 enriched in NGN2 cultures, while SLC17A7 (VGLUT1) was not detected (Figure 3C-F).
203 Surprisingly, NGN2 neurons also showed strong enrichment of several proteins typically
204 associated with GABAergic neurons at all timepoints, including SCGN, CALB2, and PVALB.

205 Immunocytochemistry confirmed PVALB expression in the majority of NGN2 neurons (Figure
206 S4B).
207 To quantitatively assess cell type specification, we performed expression-weighted
208 cell type enrichment (EWCE) analysis(Skene & Grant, 2016) on the top 5% upregulated
209 neuronal proteins for each induction for each timepoint. At all timepoints, PB-AD-specific
210 neuronal proteins showed exclusive and significant enrichment for GABAergic neurons, with
211 enrichment levels increasing until 8 WPI (Figure 2G). GABAergic subclass analysis revealed
212 strongest enrichment for VIP$^+$ interneurons from 6-10 WPI (Figure S4C). In contrast, NGN2-
213 specific proteins showed significant enrichment for glutamatergic neurons only at 6 and 10
214 WPI, while also displaying unexpected GABAergic enrichment, reaching significance at 4 and
215 10 WPI (Figure 3H). Subclass enrichment analysis revealed that this unexpected GABAergic
216 enrichment was most likely accounted for by PVALB$^+$ and VIP$^+$ interneuron-like profiles (S4C,
217 S4D). Taken together, PB-AD neurons acquire a stable GABAergic identity over time,
218 characterized by consistent expression of canonical and subtype-specific GABAergic proteins.
219 By contrast, NGN2-induced neurons exhibit a mixed molecular identity, with evidence for
220 partial GABAergic specification in addition to expected glutamatergic features.

221 *Gradual morphological development of PiggyBac Ascl1/Dlx2 neurons*
222 To examine morphological maturation of PB-AD neurons, we performed immunostaining for
223 MAP2, VGAT and VGLUT1/2 in autaptic cultures (Figure 4A). Similar to networks, PB-AD
224 neurons produced only VGAT$^+$ puncta at all timepoints (Figure 4A-C). A progressive increase
225 in dendrite length was observed during maturation (Figure 4D), accompanied by an increase
226 in the total number of VGAT$^+$ puncta per neuron and puncta densities per dendritic length
227 (Figure 4E-F). Additionally, the intensities of VGAT puncta increased over time (Figure 4G),
228 suggesting increased synaptic vesicles per synaptic terminal. Sholl analysis revealed a rise
229 in the number of arborizations during maturation (Figure 4H,I). Interestingly, growth of
230 dendritic length and complexity plateaued by 6 WPI, whereas synaptic projections continued
231 to develop until 8 and 10 WPI. Together, these results demonstrate that PB-AD neurons
232 develop complex neuronal morphologies accompanied by an increase in presynaptic
233 GABAergic terminals during maturation.

234 *Synaptic strengthening during maturation of PiggyBac Ascl1/Dlx2 neurons*
235 Next, we assessed functional maturation in autaptic neurons with voltage-clamp
236 electrophysiology. Firstly, action-potential independent spontaneous release was recorded.
237 Both miniature postsynaptic current (mPSC) frequency and amplitude increased during
238 maturation (Figure 5A-C). Next, neurons were depolarized to induce ePSCs. Across all time

239 points, 70-80% of neurons were synaptically active, producing a charge of at least 1.5 pC
240 within 70 ms after stimulation (Figure 5D). In active cells, both the amplitude and charge of
241 ePSCs increased progressively between 4 and 10 WPI (Figure 5E-G), with the most
242 pronounced change occurring from 8 to 10 WPI. Decay constants remained consistently
243 above 30 ms – characteristic of GABAergic currents (Figure 5H). Interestingly, decay kinetics
244 subtly slowed after 4 WPI, suggesting potential changes in postsynaptic receptor
245 subunits(Dixon *et al*, 2014; Zhang *et al*, 1997).

246 To evaluate the impact of maturation on short-term synaptic plasticity, we applied
247 paired-pulse stimulation at 50 ms, 200 ms, and 1000 ms intervals (Figure 5I-L). This revealed
248 modest synaptic depression which was stable throughout maturation. Only at a 1000 ms
249 interval, synaptic depression increased as neurons matured. Importantly, maturation
250 increased the size of the readily releasable pool (RRP), as determined by back-extrapolation
251 of the charge evoked by 20 Hz stimulus trains, with the biggest change occurring from 8 to
252 10 WPI (Figure 5M-O). Taken together, these findings demonstrate that PB-AD GABAergic
253 neurons develop functional, plastic synapses that strengthen during maturation.

254 *Functional maturation correlates with upregulation of proteins in presynaptic gene sets*

255 To investigate the molecular basis of synaptic maturation, we looked at the differential
256 expression of SYNGO-annotated synaptic proteins between different timepoints of
257 development (4 to 6 WPI, 6 to 8 WPI, and 8 to 10 WPI)(Koopmans *et al*, 2019a) (Figure 6A). Of
258 all 1605 SYNGO-annotated synaptic genes, 929 unique proteins were detected in PB-AD
259 cultures, of which 478 (51%) were differentially expressed in at least one time contrast
260 (Figure 6B, D-F). In NGN2 neurons, 967 unique SYNGO-annotated proteins were identified of
261 which 644 (67%) were differentially expressed in at least one time contrast (Figure 6C, Figure
262 S5A-C). In both cultures, SYNGO-annotated proteins were abundantly regulated between 4
263 and 8 WPI, while only few proteins showed altered expression between 8 and 10 WPI (Figures
264 6B-F, Supplementary table 1). This indicates that proteomic synaptic maturation plateaus
265 after 8 WPI, consistent with what was observed for neuronal-enriched protein expression.

266 To examine specifically how pre- and postsynapses develop over time, we used
267 GOAT(Koopmans, 2024a) to determine which SYNGO gene sets were enriched for
268 developmentally regulated proteins, where the contribution of each protein was weighted
269 by its $\log_2$(fold change)(Koopmans, 2024a). Strongest enrichment was observed between 4-
270 6 WPI and 6-8 WPI, which occurred exclusively in presynaptic gene sets, including *synaptic*
271 *vesicle* (*SV*), *presynaptic active zone (AZ)*, and *presynaptic membrane* (Figure 6G-L). Between 8-
272 10 WPI only *SV membrane* proteins and its mother term *presynaptic* proteins were enriched.

273 In contrast, no postsynaptic gene sets were significantly enriched in PB-AD cultures, across
274 all time contrasts. To exclude that these results were biased by a few proteins with large
275 effect sizes, additional SYNGO gene set overrepresentation analysis was performed based on
276 the number of upregulated proteins per gene set. This confirmed the exclusive enrichment
277 of presynaptic terms in PB-AD cultures (Figure S5J–L). Upregulated proteins in NGN2 cultures
278 over time similarly showed a preferential enrichment of presynaptic gene sets using GOAT
279 and SYNGO overrepresentation analyses, with no enrichment for postsynaptic gene sets
280 between 6-10 WPI. Thus, synaptic strengthening correlates with changes specifically in
281 presynaptic protein levels, while postsynaptic protein levels remain relatively stable over
282 time.

283 In order to test whether our findings on asymmetrical pre- and postsynaptic
284 maturation translate to a more physiological model, we assessed postsynaptic responses to
285 externally applied GABA in E/I networks, as excitation might alter maturation
286 profiles(Paraskevopoulou *et al*, 2019) (Figure 6M). Furthermore, we used gramicidin-
287 perforated patch to allow measurement of postsynaptic responses without influencing the
288 reversal potential for the GABA-receptor(Watanabe & Fukuda, 2015). GABA puffs were
289 applied at varying holding voltages (Figure 6N). The slope of the I/V curve voltages was
290 unaltered by maturation ($p = 0.305$), indicating that the GABAergic postsynaptic response
291 does not change during maturation under these conditions. Thus, increased synaptic strength
292 during synaptic maturation correlates with presynaptic proteomic changes, but not with
293 postsynaptic development also in E/I-networks.

294 *PiggyBac Ascl1/Dlx2 specific synaptic proteins map to cortical interneuron subtypes*

295 Finally, we investigated whether changes in PB-AD and NGN2 SYNGO-annotated proteomes
296 between 4 and 10 WPI are associated with cortical GABAergic and glutamatergic cell
297 types(Jorstad *et al*., 2023) (Figure 7A). PB-AD cultures showed upregulation of predicted
298 GABAergic and medial ganglionic eminence (MGE) and caudal ganglionic eminence (CGE)-
299 specific proteins (Figure 7B). NGN2 cultures showed upregulation of predicted glutamatergic
300 proteins (Figure 7C). Of note, PB-AD and NGN2 cultures showed upregulation of both
301 GABAergic and glutamatergic receptor subunits (Figure S6A,B), although only input of one of
302 the neurotransmitters was present per culture. Canonical subtype markers for both MGE- and
303 CGE-derived subtypes were also detected in PB-AD neurons (S6C,D).

304 To analyze lineage-specific synaptic development in more detail, we next contrasted
305 the developing (WPI 4 to WPI 10) PB-AD and NGN2 SYNGO-annotated proteomes with each
306 other to find proteins that were specifically regulated in each induction. To this end, for each

307 protein we calculated the difference between PB-AD and NGN2 in differential expression
308 between 4-10 WPI (i.e., $\log_2(FC)_{AD}$- $\log_2(FC)_{NGN2}$), and selected the 5th and 95th percentile to
309 define induction-specific synaptic proteins (Figure 7A). We then assessed whether these
310 proteins were enriched in either cortical glutamatergic or cortical GABAergic reference
311 expression profiles(Jorstad *et al*., 2023). Overall, this produced lineage-specific enrichments
312 in most gene sets. PB-AD specific synaptic proteins showed the highest GABAergic
313 enrichment in the gene sets *dense core vesicle* (*DCV*), *SV*, *synaptic signalling*, *metabolism* and
314 *presynaptic process* (Figure 7D-E). Conversely, NGN2-specific synaptic proteins that belonged
315 to *synaptic signalling, SV, organization* and *specialization* showed the highest glutamatergic
316 enrichment (Figure 7F-G).
317 As synaptic gene expression profiles have been shown to reflect neuronal
318 subtypes(Roig Adam *et al*, 2023), we queried whether synaptic proteins that specifically
319 increase in PB-AD or NGN2 cultures show enrichment for neuronal (sub)types. In EWCE
320 analysis, the PB-AD-specific synaptic proteins were enriched in GABAergic neurons (Figure
321 7H), specifically VIP$^+$, SST$^+$, PAX6$^+$ and LAMP5$^+$ interneurons, but not PVALB$^+$ neurons (Figure
322 7I). NGN2-specific synaptic proteins were enriched in glutamatergic subtypes (IT, L4 IT, L5 ET,
323 L6 CT, and L6b) but also in GABAergic subtypes (Figure 7J), particularly VIP$^+$ interneurons
324 (Figure 7K). Together, these data indicate that PB-AD-based induction leads to GABAergic
325 synaptic specialization with molecular profiles resembling CGE- and MGE-derived
326 interneurons, whereas NGN2 induction leads to induction of neurons that also contain typical
327 GABAergic proteins.
328
329 **Discussion**

330 *Summary*
331 In this work, we present a single-step, transposon-based GABAergic differentiation method,
332 which uses a single vector to overexpress Ascl1/Dlx2, and we provide a detailed
333 characterization of these GABAergic neurons at different developmental timepoints using
334 mass spectrometry proteomics, immunocytochemistry, and patch-clamp electrophysiology.
335 This method is applicable across different genetic backgrounds and produces exclusively
336 GABAergic neurons with a proteomic profile that maps to different cortical interneuron
337 subtypes, particularly VIP+ neurons. Synapses display GABAergic properties such as
338 picrotoxin-sensitive, slowly decaying, evoked postsynaptic currents and short-term
339 depression, similar to primary GABAergic neurons(Ikeda *et al*, 2008; Jiang *et al*, 2000; Lambert
340 & Wilson, 1994; Pearce *et al*, 1995). During development, synapses gradually increase in

synaptic strength, which at earlier timepoints correlates with enhanced expression of specific presynaptic gene sets associated with the active zone, synaptic vesicle, and presynaptic membrane. In contrast, little functional and proteomic changes occur in the postsynapse. Late in development synaptic strength continues to increase, with only minor changes at the proteomic level. PB-AD neurons can be combined with NGN2 neurons to form networks of predefined E/I ratios with corresponding synapse ratios. Taken together, transposon-based GABAergic induction yields pure GABAergic neurons with improved synaptic properties that can be used to build balanced excitation/inhibition networks, for instance for disease modelling in those (many) cases where E/I disbalance has been proposed as a disease mechanism.

PiggyBac Ascl1/Dlx2 neuronal induction produces exclusively GABAergic neurons

By employing autaptic neurons we were able to detect synaptic output on a single neuron scale, which allowed us to accurately quantify lineage specification and demonstrate how pure GABAergic transposon-based induction is compared to lentiviral strategies. Previous studies using a lentiviral approach also detected non-GABAergic currents(Gonzalez-Ramos *et al*, 2021) and reported expression of glutamatergic genes(Barretto *et al*, 2020; Song *et al*, 2021), while others focused on measurements in E/I-networks(Mossink *et al*., 2022; Yang *et al*., 2017b) or recorded under conditions that blocked glutamatergic transmission(Marcó de la Cruz *et al*, 2024; Sanchez-Priego *et al*, 2022), making it difficult to compare with our results. As Ascl1 expression, by itself, induces glutamatergic differentiation(Chanda *et al*, 2014; Wu *et al*, 2024), the balance of Ascl1 and Dlx2 expression is likely important in steering differentiation towards a GABAergic fate. The design of our transposon-based induction incorporates multiple features to facilitate this and thereby avoids unwanted glutamatergic specification. Firstly, both factors are present in one cassette and transcribed from a bidirectional promotor. Secondly, a shared integration site could prevent position effects(Gierman *et al*, 2007). Lastly, insulator elements may reduce gene silencing, which is observed for lentiviral cargo(Cabrera *et al*., 2022; Gödecke *et al*, 2017; He *et al*, 2005; Kwak *et al*, 2024; Liew *et al*, 2007; Wolf & Goff, 2009; Yao *et al*., 2004), and less so for transposon delivered transgenes(Ng *et al*., 2021).

Proteomic profiles of PiggyBac Ascl1/Dlx2 neurons map to cortical interneuron subtypes

Cell type enrichment analysis revealed that neuronal proteins that are higher expressed in PB-AD cultures are significantly enriched for GABAergic neurons at all timepoints, with specific enrichment for VIP^+ interneurons from 6 WPI onwards. Zooming in on synaptic proteins that are upregulated specifically in PB-AD cultures between 4-10 WPI showed

375 significant enrichment for all GABAergic interneuron subtypes except PVALB$^+$, suggesting
376 specification towards both MGE- and CGE-derived neurons. In a previous single-cell RNA-
377 sequencing study of lenti-AD induced neurons, predominantly SST$^+$ neurons were detected
378 at 4 WPI, but later time points were not investigated(Allison *et al*, 2021). Perhaps CGE markers
379 only appear further along the maturation process, or transcriptomics do not accurately
380 recapitulate the molecular identity of these neurons(Lindhout *et al*, 2020; Moritz *et al*, 2019;
381 Titlow *et al*, 2023).
382 NGN2-induction exhibited a mixed glutamatergic and GABAergic molecular identity,
383 although virtually no VGAT puncta were identified and only glutamatergic ePSCs were
384 recorded, consistent with previous reports(Bullmann *et al*, 2024; Fenske *et al*, 2019; Lin *et al*,
385 2021; Meijer *et al*., 2019; Nehme *et al*, 2018; Rhee *et al*, 2019; van Berkel *et al*, 2024). Thus,
386 its proteomic profile does not translate to mixed functional identity, making it a good model
387 for pure glutamatergic neurons.

388 *Enhanced expression of proteins in presynaptic gene sets during synaptic maturation*
389 Our multilevel analysis of GABAergic cultures at different time points between 4 and
390 10 WPI, combining patch-clamp electrophysiology, immunocytochemistry, and mass spec
391 proteomics, revealed the following insights about synapse maturation: Firstly, synaptic
392 strength increased approximately 3-fold during this period. A comparable increase in mPSC
393 frequency and RRP suggests that this is due to an increase in the strength and/or number of
394 presynaptic projections, which is supported by VGAT immunocytochemistry. Similar
395 development has been described for directed-differentiation and safe-harbor AD GABAergic
396 autaptic neurons(Meijer *et al*., 2019; Rhee *et al*., 2019).
397 Secondly, we observed a stark difference between pre- and postsynaptic development.
398 Strong upregulation of *AZ-*, *SV-* and *presynaptic membrane* proteins occurred, while expression
399 changes in proteins in postsynaptic gene sets were minimal. Current responses to GABA puffs
400 remained constant over time, indicating that functional postsynapses already exist at 4 WPI
401 and the expression of GABA receptors remains unaltered at subsequent weeks. This fits with
402 the notion that expression of postsynaptic neurotransmitter receptors precedes presynaptic
403 innervation(Friedman *et al*, 2000; Kwon & Sabatini, 2011; Mammen *et al*, 1997; Petralia,
404 2012; Richards *et al*, 2005). Release from presynaptic projections subsequently induces
405 clustering of postsynaptic molecules, initiating postsynaptic maturation(Andreae & Burrone,
406 2015; Friedman *et al*., 2000; Harms *et al*, 2005; Okabe *et al*, 2001; Sanes & Lichtman, 1999).
407 Indeed, alignment of the pre- and postsynapse and/or clustering of postsynaptic receptors
408 could explain the 1.5-fold increase in mPSC amplitude with the total number of GABA

409 receptors remaining constant. A similar asymmetric proteomic development of the pre- and
410 postsynapse was observed in NGN2 neurons and has previously also been described for
411 directed differentiation of iPSC-derived neurons(Nadadhur *et al*, 2017; Togo *et al*, 2021).
412 Thirdly, functional development follows molecular development with a delay.
413 Proteomic changes abruptly stop after 8 WPI, while the number of synapses and synaptic
414 strength continues to increase beyond this point. Possibly, the bulk of *AZ, SV* and *presynaptic*
415 *membrane* proteins that are upregulated until 8 WPI are needed to create functional
416 presynapses. Enhancement of GABAergic synaptic strength after this timepoint could rely on
417 cell intrinsic and/or astrocyte-induced(Chung *et al*, 2015; Elmariah *et al*, 2004; Liu *et al*, 2022;
418 Liu *et al*, 2021; Noriega-Prieto & Araque, 2021) structural rearrangement, as well as
419 posttranslational modifications of synaptic proteins, which can occur via various
420 mechanisms. For example, posttranslational modification, mediated by e.g. ERK, PKC, PKA,
421 CaMKII and/or RhoA/ROCK signaling(Bright & Smart, 2013; Cui *et al*, 2008; Farzana *et al*,
422 2016; Flores *et al*, 2015; Ghosh *et al*, 2016; Hao *et al*, 2023; Hausrat *et al*, 2015; Houston *et*
423 *al*, 2009; Lützenkirchen *et al*, 2024a; Lützenkirchen *et al*, 2024b; Nakamura *et al*, 2015; Song
424 & Augustine, 2023; Tyagarajan *et al*, 2013; Tyagarajan *et al*, 2011; Vaughan *et al*, 1998), affects
425 many pre- and postsynaptic proteins, including gephyrin(Flores *et al*., 2015; Ghosh *et al*.,
426 2016; Lorenz-Guertin & Jacob, 2018; Tyagarajan *et al*., 2013; Tyagarajan *et al*., 2011), GABA-
427 receptors(Bright & Smart, 2013; Farzana *et al*., 2016; Hao *et al*., 2023; Hausrat *et al*., 2015;
428 Houston *et al*., 2009; Lorenz-Guertin & Jacob, 2018; Lützenkirchen *et al*., 2024b; Nakamura
429 *et al*., 2015), SV-anchored synapsins(Cui *et al*., 2008; Song & Augustine, 2023) and
430 microtubules along with their associated proteins(Heisler *et al*, 2011; Jacob *et al*, 2008;
431 Lorenz-Guertin & Jacob, 2018; Prag *et al*, 2007; Velasco *et al*, 2023; Waites *et al*, 2021). These
432 modifications influence the localization and functional properties of these proteins, thereby
433 modulating synaptic strength. Additionally, synaptic strength can be regulated by (trans-
434 synaptic) alignment of functionally related proteins in nanodomains and nanocolumns,
435 enhancing their cooperative interactions(Biederer *et al*, 2017; Olah *et al*, 2023; Sanderson *et*
436 *al*, 2020; Scimemi & Diamond, 2012; Südhof, 2018, 2021; Tang *et al*, 2016). Of the few
437 proteins that were upregulated – or for the first time detected – in PB-AD neurons at 10 WPI
438 (Table S1), we found several cell adhesion molecules (CAMs) (CNTNAP4, SLITRK1, CDH1,
439 EPHA7, ITGB3, NPTX2, ITGA2, ELFN1, IGSF8 and CNTNAP1)(Beuter *et al*, 2016; Fiederling *et*
440 *al*, 2011; Karayannis *et al*, 2014; Li *et al*, 2020; Park & Goda, 2016; Ray & Treloar, 2012; Sia *et*
441 *al*, 2007; Stachniak *et al*, 2019; Um *et al*, 2014; Wiera *et al*, 2022), extra cellular matrix (ECM)
442 proteins (ITGB3, ITGA2, TNC, GPR158 and RELN) (Condomitti *et al*, 2018; Park & Goda, 2016;

443 Quattrocchi *et al*, 2002; Tucić *et al*, 2021; Wiera *et al*., 2022), and proteins involved in receptor
444 clustering (NPTX2, SLITRK1, PRRT1, ELFN1)(Martin *et al*, 2021; Matsunaga & Aruga, 2021;
445 O'Brien *et al*, 1999; Yim *et al*, 2013). Some of which are known to strengthen GABAergic
446 transmission(Beuter *et al*., 2016; Karayannis *et al*., 2014). Altogether, this suggests that
447 maturation and synaptic strengthening in iPSC-derived neuronal synapses depends on
448 presynaptic development driven by enhanced expression of multiple presynaptic gene sets
449 and alignment/reorganisation of pre- and postsynapse driven by synapse-organising genes.

450 *A versatile in vitro model for studying the role of inhibition in brain disease*
451 Dysfunction of inhibitory neurons and E/I disbalance are common aspect of
452 neurodevelopmental and neurodegenerative disorders(Gabitto *et al*, 2023; Goel *et al*, 2018;
453 Hijazi *et al*, 2020; Malwade *et al*, 2022; Mossner *et al*, 2020; Palop *et al*, 2007b; Zott *et al*,
454 2018). Given the purity of the GABAergic cultures produced with the PB-AD protocol, neurons
455 generated with this method provide a versatile model to study the role of inhibition and E/I
456 disbalance in these disorders using a human, and patient-own, genetic background.
457 Compared to a safe harbour approach, our method is directly applicable to patient derived
458 iPSCs, which makes it time and cost efficient, and prevents the introduction of clonal gene
459 editing effects. The reliable production of GABAergic autaptic cultures allows for a detailed
460 assessment of interneuron synaptic properties, such as priming, fusion and synaptic plasticity
461 in patient cell lines(Østergaard *et al*, 2025; Öttl *et al*, 2024; van Boven *et al*, 2024). Application
462 to disease-lines will be important steps to substantiate the full potential of this method. To
463 this end, PB-AD neurons can be mixed with NGN2 neurons at defined ratios, enabling
464 accurate modelling of E/I networks at any ratio, including those found in the human
465 brain(Bakken *et al*., 2021; Fang *et al*., 2022; Loomba *et al*., 2022).
466

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Declaration of interest

The authors declare no competing interests.

Author contributions

M.E.W., and J.M.C.M. designed and produced the PiggyBac construct
T.W.v.V, M.A.v.B., K.I.M., R.F.T., A.B.S., R.E.v.K, M.V. and L.N.C. designed the experiments
T.W.v.V, M.A.v.B. and J.S. performed and maintained neuronal inductions and cultures
T.W.v.V M.A.v.B. performed the patch-clamp experiments with contributions of J.S. to Fig. 1 and C.F. to Fig. S2
T.W.v.V, M.A.v.B.,. performed the immunocytochemistry experiments with contributions of J.S to Fig. 1
K.I.M., and F.K. performed the proteomics experiments and analysis
T.W.V.V, M.A.v.B., K.I.M., R.E.v.K, M.V. and L.N.C. designed figures and wrote the manuscript with input from all authors.

Methods

Key resources table

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
MAP2	Merck Millipore	(Millipore Cat# AB5543, RRID:AB_571049)
VGAT	Synaptic Systems	(Synaptic Systems Cat# 131 002, RRID:AB_887871)
VGLUT1	Antibodies Inc.	(Antibodies Incorporated Cat# 75-066, RRID:AB_2187693)
VGLUT2	Antibodies Inc.	(Antibodies Incorporated Cat# 75-067, RRID:AB_2239153)

NeuN	Merck Millipore	(Millipore Cat# ABN78, RRID:AB_10807945)
Parvalbumin	Synaptic Systems	(Synaptic Systems Cat# 195 004, RRID:AB_2156476)
Bacterial and virus strains		
FUW-TetO-*Ascl1*-T2A-puro	Addgene	RRID:Addgene_97329
FUW-TetO-*Dlx2* -IRES-hygro	Addgene	RRID:Addgene_97330
FUW-M2rtTA	Addgene	RRID:Addgene_20342
Deposited data		
PRIDE dataset "Transposon-based single-step induction of human GABAergic neurons reveals enhanced expression of presynaptic gene sets during synaptic maturation"	This study	N/A
Transcriptomic cytoarchitecture reveals principles of human neocortex organization	Jorstad, et al.(Jorstad *et al.*, 2023)	RRID:SCR_016152
Experimental models: Cell lines		
BiONI010-C-10	EBiSC	RRID:CVCL_RM84
BioNi010-C-13	EBiSC	RRID:CVCL_RF90
Kolf2.1J	Jackson Laboratory	RRID:CVCL_B5P3
GM23973	Coriell	RRID:CVCL_BW42
Recombinant DNA		
PB-TO-ASCL1-DLX2	This study	RRID:Addgene_182307
Transposase	This study	N/A
Software and algorithms		
DIA-NN 1.8.1	Demichev, et al (2020,2022)(Demichev *et al*, 2020; Demichev *et al*, 2022)	
MS-DAP 1.0.5	Koopmans, et al. 2023(Koopmans *et al*, 2023)	

DEqMS	Zhu, et al, 2020(Zhu *et al*, 2020)	
GOAT	Miedema, et al. 2022(Koopmans, 2024b)	
SynGO	Koopmans, et al. 2019(Koopmans *et al*, 2019b)	

496

497 *iPSCs origin and culture*

498 Unless stated otherwise, the BiONi010-C-10 stem cell line (EBISC, RRID:CVCL_RM84) was
499 used for all experiments in this study. For glutamatergic induction, a gene-edited variant of
500 the same line containing an integrated NGN2-casette was used (EBISC, RRID:CVCL_RF90). As
501 a genetically independent control the KOLF2.1J (JAX, JiPSC1000, RRID:CVCL_B5P3) and
502 GM23973 (Coriell, RRID:CVCL_BW42) lines were used. All iPSCs were maintained on Matrigel
503 (Cornig) or Geltrex (Fisher Scientific)-coated dishes in Essential 8 (Gibco) or Essential 8 Flex
504 (Gibco) medium and passaged with EDTA and replated in the culture medium supplemented
505 with ROCK inhibitor Y27632 (5 µM, Tetu bio).

506 *Lentiviral infection*

507 Ultrahigh titre lentiviral particles were generated by Alstem (Richmond, CA, USA) from FUW-
508 M2rtTA (Addgene, #20342, RRID:Addgene_20342), FUW-TetO-*Ascl1*-T2A-puro (Addgene
509 #97329, RRID:Addgene_97329), and FUW-TetO-*Dlx2* -IRES-hygro (Addgene #97330,
510 RRID:Addgene_97330). For *Ascl1*+Forskolin, iPSCs were infected with only FUW-M2rtTA and
511 TetO-*Ascl1*-Puro, for *Ascl1* + *Dlx2* induction, iPSCs were infected with all three lentiviruses.
512 For both lentiviral induction methods, 24 hours after dox induction, puromycin (1 µg/ml)
513 selection was performed. For lentiviral *Ascl1* + *Dlx2* induction, additional hygromycin (75
514 µg/ml) selection was performed. For both selection regimes an uninfected control well was
515 included to confirm successful selection before proceeding towards induction.

516 *PiggyBac transfection*

517 To prepare for PiggyBac transfection, iPSCs were released with accutase and plated as single
518 cells on a Matrigel-coated 6-well plate in E8 + ROCK Inhibitor Y27632 at a density of 1500k
519 per well. Cells were placed in the incubator to adhere for 1 to 2 hours. A total of 3 µg of DNA
520 containing the *Ascl1* + *Dlx2* PiggyBac transposon (Presented here; available on Addgene,

521 182307, RRID:Addgene_182307) and transposase constructs (extended data 1) at a 1:3 molar
522 ratio was prepared in 100 µL of opti-MEM (GIBCO, 31985062). To another 100 µL op opti-
523 MEM 5 µL of Lipofectamine STEM (Invitrogen, STEM00001) was added. Opti-MEM
524 preparations were quickly mixed by pipetting, after which the mixture was incubated at RT
525 for 15 to 30 minutes during which cells received fresh E8 + ROCK Inhibitor Y27632 to wash
526 away non-adherent cells. The opti-MEM solution was then added to the cells in a dropwise
527 fashion. 24 hours post transfection, selection with puromycin (1 µg/ml) was initiated to select
528 only for cells containing the transposon, and selection was repeated every 3-4 days.

529 *PB-AD GABAergic neuronal induction*

530 PB-AD positive iPSCs were released with Accutase (Merck) on day post induction (DPI) 0 and
531 replated with at an approximate density of 3.500 cells/cm^2 in N2 medium (DMEM/F12
532 medium, Life technologies) containing Glutamax (200 mM, Life Technologies), dextrose (0.3%,
533 Life Technologies) N2 supplement B (StemCell Technologies), Pen/Strep (0.1%, Gibco), ROCK
534 inhibitor Y27632 (10 µM, Tetubio) and doxycycline hyclate (2 µg/mL) onto Matrigel (Cornig)
535 or Geltrex (Fisher Scientific) coated dishes. On DPI 1, medium was refreshed using the same
536 composition without ROCK inhibitor Y27632. On DPI 2, the medium was refreshed once more
537 with the same composition as on DPI 1, with the addition of 5-Fluoro-2'-deoxyuridine (FUDR)
538 (10 µM, Sigma-Aldrich) or Cytosine β-D-arabinofuranoside (AraC, 20 µM, Sigma-Aldrich) to
539 remove proliferative cells. On DPI 3, neurons were released with accutase, pelleted, and
540 resuspended and plated in Neurobasal medium (Life Technologies) supplemented with
541 Glutamax (200 mM), B27 (0.1%) Pen-Strep (0.1%), fetal bovine serum (0.5%), BDNF (10 ng/ml,
542 Peprotech), CNTF (10ng/ml, Peprotech), GDNF (10 ng/ml, Peprotech) and doxycycline hyclate
543 (2 µg/mL; Sigma-Aldrich). Neurons were plated to the required respective preparations (see
544 *Autaptic culture* and *Network culture*).

545 *Glutamatergic neuronal induction*

546 For glutamatergic induction, Bioni010-C-13 iPSCs were released with Accutase (Merck) on
547 DPI 0 and replated with at an approximate density of 3.500 cells/cm^2 in N2 medium
548 (DMEM/F12 medium, Life technologies) containing Glutamax (200 mM, Life Technologies),
549 dextrose (0.3%, Life Technologies) N2 supplement B (StemCell Technologies), Pen/Strep
550 (0.1%, Gibco) and doxycycline hyclate (2 µg/mL; Sigma-Aldrich) combined with dual-SMAD
551 inhibitors LDN193189 (100 nM, Stemgent), SB431542 (10 µM, Tocris Bioscience), and XAV939
552 (2 µM, Stemgent) NT3 (10 ng/ml, Peprotech) and doxycycline hyclate (2 µg/mL) onto Matrigel
553 (Cornig) or Geltrex (Fisher Scientific) coated dishes. On DPI 1, medium was refreshed using
554 the same composition without ROCK inhibitor Y27632. On DPI 2, the medium was refreshed

555 once more with the same composition as on day 2, with the addition of 5-Fluoro-2'-
556 deoxyuridine (FUDR) (10 µM, Sigma-Aldrich) or Cytosine β-D-arabinofuranoside (AraC, 20 µM,
557 Sigma-Aldrich) to remove proliferative cells. On DPI 3, neurons were released with accutase,
558 pelleted, resuspended and plated in Neurobasal medium (Life Technologies) supplemented
559 with Glutamax (200 mM), B27 (0.1%) Pen-Strep (0.1%), foetal bovine serum (0.5%), BDNF (10
560 ng/ml, Peprotech), CNTF (10ng/ml, Peprotech), GDNF (10 ng/ml, Peprotech) and doxycycline
561 hyclate (2 µg/mL; Sigma-Aldrich). Neurons were plated to the required respective
562 preparations (see *Autaptic culture* and *Network culture*).

563 *Lentiviral GABAergic induction*

564 In general, lentiviral GABAergic induction protocols followed a similar workflow as PB-AD
565 induction. To better adhere to established protocols(Mossink *et al.*, 2022; Yang *et al.*, 2017a),
566 the medium composition differed at certain steps (Figure 1H). For Ascl1 + Forskolin induction,
567 from DPI 0 onwards, Forskolin (10 µM, Merck) was added to the medium up to DPI 14.
568 Furthermore, from DPI0 onwards non-essential amino acids (1:100, Sigma) were added up to
569 day DPI 14. BDNF (10 ng/ml) and NT3 (10 ng/ml) were present from DPI1 onwards. For
570 lentiviral *Ascl1* + *Dlx2* induction BDNF (10 ng/ml) and NT3 (10 ng/ml) were added from DPI
571 0 onward, as well. Furthermore, laminin (1µg/ml, Sigma-Aldrich), cyclic AMP (1 µM, Sigma-
572 Aldrich), and Ascorbic Acid(200 µM, Sigma-Aldrich), were added to the medium at all
573 subsequent refreshments to improve viability.

574 *Autaptic culture*

575 Neurons were plated at a density of ~ 400 cells / cm^2 on micro-islands prepared from rat
576 glial cells plated on agarose-coated coverslips stamped with a custom stamp in Poly-D-
577 Lysine (0.1 mg/ml, Sigma), rat tail collagen (0.7 mg/ml, Corning) and Fibronectin (100 µg/ml,
578 Corning) in acetic acid (10 mM, sigma). Glial islands were prepared approximately 7 days
579 before plating neurons and were treated with AraC (20 µM, Sigma-Aldrich) before plating
580 neurons. Autaptic cultures were refreshed every 7 days with a ~50% media refreshment, with
581 the same medium as used for plating neurons, but omitting doxycycline hyclate (except for
582 Figure 1E-G, where doxycycline hyclate was added up to DPI 14).

583 *Network culture*

584 Neurons were plated at a density of ~ 7000 cells / cm^2 on coverslips covered with a glial-
585 monolayer prepared from rat astrocytes a week in advance and treated with Cytosine β-D-
586 arabinofuranoside (20 µM, Sigma-Aldrich) 24-48 hours before plating neurons. Networks

587 cultures were refreshed with a ~50% media refreshment every 3-4 days, with the same
588 medium as used for plating neurons, but omitting doxycycline hyclate.

589 *Electrophysiology*

590 Whole-cell voltage-clamp recordings ($V_m = -70$ mV) were performed on autaptic neurons,
591 with borosilicate glass pipettes (2 – 5MΩ) filled with (in mM) 136 KCl, 17.8 HEPES, 1 EGTA,
592 0.6 $MgCl_2$, 4 ATP-Mg, 0.3 GTP-Na, 12 phosphocreatine-K_2 and 50 units/mL phosphocreatine
593 kinase (pH = 7.30, 290 mOsmol). The external solution contained in mM: 10 HEPES, 10
594 glucose, 140 NaCl, 2.4 KCl, 4 $MgCl_2$, and 4 $CaCl_2$ (pH = 7.30, 290 mOsmol). Experiments were
595 performed at room temperature (~22°C using a MultiClamp700B amplifier (Axon
596 Instruments) and Digidata 1440A digitizer under control of Clampex 10 software (Molecular
597 devices). Only cells with an access resistance < 15MΩ (80% compensated) and leak current
598 of <300 pA were included. Synaptic responses were elicited by 0.5 ms depolarization to
599 30 mV.

600 For GABA puffs, perforated patch recordings were produced by filling the patch pipette
601 (in mM) 140 KCl, 10 HEPES, gramicidin (100 µg/ml) and allowing cells to perforate for 15-30
602 minutes after reaching a GΩ seal to < 100 MΩ series resistance. Puff pipettes filled with 100
603 µM GABA in ACSF were positioned near the soma, at approximately 25 µm distance. 100 ms
604 puffs were applied at -110, -90, -70, -50, -30 and -10 mV holding voltages to induce GABAergic
605 currents.

606 *Pharmacology*

607 To Block GABA-currents, picrotoxin (100 µM, Hello Bio) was used. A 100 mM stock was
608 prepared in DMSO and was added to the bath to reach the final concentration. To block
609 glutamatergic currents, AP-V (100 µM, R&D systems) and DNQX (40 µM, Tocris) were used.
610 For DNQX, A 1000x of stock of each was prepared in DMSO. For AP-V, the stock was prepared
611 in water.

612 *Analysis electrophysiological data.*

613 Offline analysis was performed using custom-written programs(Huson & Cornelisse, 2019)
614 in Matlab (Mathworks). Experimental conditions were blinded during analysis. In all figures,
615 stimulation artefacts have been removed. For evoked release during 20 Hz stimulation, back-
616 extrapolation of linear fits from the last 20 pulses of the cumulative charge was used to
617 estimate the RRP (y-intercept)(Neher, 2015).

618 *Immunocytochemistry and morphological analysis*

619 Neurons were fixed in ice cold 100% methanol (VWR) for 15 minutes at 4°C, blocked with
620 2.5% normal goat serum (NGS, Life Technologies) and 0.1% Triton X-100 in PBS for
621 45 minutes and incubated with primary antibodies in PBS with 2.5% NGS and 0.1% Triton X-
622 100 overnight at 4°C. The following primary antibodies were used: chicken anti-MAP2
623 (1:1000, Merck AB5543, RRID:AB_571049); rabbit anti-VGAT (1:2000, SySy #131 002,
624 RRID:AB_887871), mouse anti-VGlut1 (1:250, NeuroMab clone N28/9, Antibodies inc. 75-066,
625 RRID:AB_2187693), mouse anti-VGlut2 (1:250, NeuroMab clone N29/29, Antibodies inc. 75-
626 067, RRID:AB_2239153), Rabbit anti-NeuN (1:500, Merck ABN78, RRID:AB_10807945) and
627 anti-Parvalbumin (1:500, SySy #195 004, RRID:AB_2156476). After washing with PBS the next
628 day, cells were incubated for 1 h at room temperature with secondary antibodies
629 conjugated to Alexa dyes (1:1000, Invitrogen Molecular Probes), washed again and mounted
630 with DABCO-Mowiol (Invitrogen). Images were acquired at 1024x1024 pixels on a Nikon
631 Eclipse Ti confocal laser scanning microscope (40× objective; NA 1.3) with NIS-Elements
632 software. Z-stacks were produced at a 0.5 µm step-size until no more puncta and/or dendrites
633 were in focus. Confocal settings were kept constant for all scans within an experimental
634 week. Analysis of neuronal morphology was performed on maximum-intensity projections
635 using the automated image analysis routine SynD(Schmitz *et al*, 2011) for autaptic neurons
636 and a custom ImageJ workflows for network analysis, in either case, for VGAT and VGLUT
637 puncta counts, only puncta on dendrites were counted.

638 *Statistics of electrophysiological and morphological data*

639 Statistical testing was performed in MATLAB and GraphPad Prism For descriptive statistics
640 (Figure 1) the likelihood of normality vs lognormality was first calculated; for normally
641 distributed data, the arithmetic mean and standard deviation were calculated. For
642 lognormally distributed data, the geometric mean and geometric SD factor were calculated,
643 instead. In autaptic development timelines (Figure 4&5), to test general developmental
644 trajectories, nonparametric Spearman correlations were computed with a two-tailed test for
645 significance and a 95% confidence interval. For timepoint comparisons, Kruskal-Wallis
646 ANOVAs were performed with Dunn's multiple comparisons test. Pairwise comparisons were
647 made between 4 and 6, 6 and 8, and 8 and 10 WPI. #, ##, ###, #### and *ns* represent results
648 of spearman correlation results, *, **, ***, **** and ns represent Kruskal-Wallis ANOVA results.
649 *ns* and ns represent non-significant results. Single, double, triple and quadruple marks
650 represent $p < 0.05$, $p < 0.01$, $p < 0.001$ and $p < 0.0001$, respectively. GABA-puff responses (figure
651 6O) were fitted using a first-order polynomial linear fit and an extra sum-of-squares F-test
652 was used to determine whether GABA responses were identical throughout development. In

653 plots, unless stated otherwise, the lines in boxplots represent the median value. Crosses
654 represent the mean value. Boxes represent 50% off the values. Circular markers represent
655 individual observations.

656 *Cell pellet harvesting for MS*

657 Cells were washed three times with 1 ml sterile Dulbecco's PBS (Gibco), whereof first twice
658 at 37°C and finally once at 4 °C. Cultures were kept on ice, scraped off using VWR cell lifters,
659 and harvested in 1.5 ml protein LoBind Eppendorf tubes (VWR). Pellets were obtained by
660 centrifugation at 1,000 × g for 5 minutes at 4 °C. Supernatant was removed and pellets were
661 kept at -80 °C before subsequent sample preparation.

662 *MS sample preparation*

663 MS sample preparation was performed following the DNA micro spin column suspension
664 trapping protocol(Thanou *et al*, 2023), with some minor adaptations. Cell pellets were
665 extracted and reduced in 6% SDS buffer, containing 50 mM Tris-HCl (pH 8) and 5 mM tris(2-
666 carboxyethyl)phosphine (TCEP), by incubation at 55°C for 15 minutes in a thermomixer set
667 to 1400 RPM. Free sulfhydryl groups were alkylated by incubation with 20 mM methyl
668 methanethiosulfonate (MMTS; 200 mM stock solution) for 15 minutes at RT. Insoluble debris
669 was cleared by centrifugation at 10000g for 1 minute at RT and the supernatant was
670 transferred to a new tube (Eppendorf). Next, samples were acidified by addition of 1.1%
671 phosphoric acid (12% stock solution), mixed with six volumes of binding/washing buffer
672 (90% methanol and 100mM Tris-HCl, pH 8) and loaded onto a plasmid DNA micro column
673 (HiPure from Magen Biotechnology). The protein particulate was retained on the column
674 upon centrifugation at 1400x g for 1 minute and the columns were washed four times with
675 binding/washing buffer. Columns were transferred to a new tube (Eppendorf), supplemented
676 with 500 ng Trypsin/Lys-C (Promega) in 50 mM NH4HCO3 and incubated overnight at 37°C
677 in a humidified incubator. Tryptic peptides were eluted and pooled by subsequent addition
678 of 50 mM NH4HCO3, 0.1% formic acid and 0.1% formic acid in acetonitrile. Collected peptides
679 were dried by SpeedVac and stored at -80°C.

680 *LC-MS Analysis*

681 Each sample of tryptic digest was redissolved in 0.1% formic acid and the peptide
682 concentration was determined by tryptophan-fluorescence assay(Wiśniewski & Gaugaz,
683 2015); 75 ng of peptide was loaded onto an Evotip Pure (Evosep). Peptide samples were
684 separated by standardized 30 samples per day method on the Evosep One liquid
685 chromatography system, using a 15 cm × 150 µm reverse-phase column packed with 1.5 µm

686 C18-beads (EV1137 from Evosep) connected to a 20 µm ID ZDV emitter (Bruker Daltonics).
687 Peptides were electro-sprayed into the timsTOF Pro 2 mass spectrometer (Bruker Daltonics)
688 equipped with CaptiveSpray source and measured with the following settings: Scan range
689 100-1700 m/z, ion mobility 0.65 to 1.5 Vs/cm2, ramp time 100 ms, accumulation time 100
690 ms, and collision energy decreasing linearly with inverse ion mobility from 59 eV at 1.6
691 Vs/cm2 to 20 eV at 0.6 Vs/cm2. Operating in dia-PASEF mode, each cycle took 1.38 s and
692 consisted of 1 MS1 full scan and 12 dia-PASEF scans. Each dia-PASEF scan contained two
693 isolation windows, in total covering 300-1200 m/z and ion mobility 0.65 to 1.50 Vs/cm2. Dia-
694 PASEF window placement was optimized using the py-diAID tool(Skowronek *et al*, 2022). Ion
695 mobility was auto calibrated at the start of each sample (calibrant m/z, 1/K0: 622.029, 0.992
696 Vs/cm2; 922.010, 1.199 Vs/cm2; 1221.991, 1.393 Vs/cm2).

697 *MS data Analysis*

698 DIA-PASEF raw data were processed with DIA-NN 1.8.1(Demichev *et al*., 2020; Demichev *et*
699 *al*., 2022). An in-silico spectral library was generated from the uniprot human reference
700 proteome (SwissProt and TrEMBL, canonical and additional isoforms, release 2023-2) using
701 Trypsin/P digestion and at most 1 missed cleavage. Fixed modification was set to beta-
702 methylthiolation(C) and variable modifications were oxidation(M) and N-term M excision (at
703 most 1 per peptide). Peptide length was set to 7-30, precursor charge range was set to 2-4,
704 precursor m/z was limited to 280–1220, both MS1 and MS2 mass accuracy were set to 15
705 ppm, scan window was set to 9, double-pass-mode and match-between-runs were enabled.
706 Protein identifiers (isoforms) were used for protein inference. All other settings were left as
707 default.

708 MS-DAP 1.0.5(Koopmans *et al*., 2023) was used for downstream differential
709 abundance analyses using the DIA-NN results. Filtering and normalization was applied to
710 respective samples per statistical contrast. Peptide-level filtering was configured to retain
711 only peptides identified in at least 4 samples in both experimental conditions (within current
712 contrast) and only proteins with 2 valid peptides were retained. Next, peptide abundance
713 values were normalized by minimizing the mode $\log_2$(FC) between sample pairs (MWMB
714 algorithm), followed by protein-level mode-between normalization. The DEqMS(Zhu *et al*.,
715 2020) algorithm was used for statistical analysis and resulting p-values were adjusted for
716 multiple testing using the Benjamini–Hochberg False Discovery Rate (FDR) procedure. To
717 investigate proteins with strong differences in detection rates between conditions, e.g.
718 consistently detected in one condition but (near) absent in another, the MS-DAP differential
719 detection test was applied to all proteins that were observed with at least 2 peptides in at

720 least 4 samples in either condition (i.e. confidently detected proteins). Using the default MS-
721 DAP workflow, we merged differential detection (DD) results into the DEqMS result table for
722 the subset of proteins that had both an absolute DD z-score of at least 6 and a smaller
723 adjusted p-value in DD (or no p-value from DEqMS due to a lack of data points in either
724 condition).

725 *Expression-weighted cell type enrichment analysis*

726 Cell type enrichment analysis gives insight into the cell types that potentially drive
727 differential expression. EWCE uses single-cell RNA-sequencing data to generate a probability
728 distribution associated with a gene list having an average level of expression within a
729 cell(Skene & Grant, 2016). Although it's based on RNA expression levels, it can also be
730 applied to proteomics data(Miedema *et al*, 2022). We used published single nucleus RNA-
731 sequencing data (49,495 nuclei) from human cortical brain regions – including middle
732 temporal gyrus, anterior cingulate cortex, primary visual cortex, primary motor cortex, primary
733 somatosensory cortex and primary auditory cortex – published by Jorstad et al(Jorstad *et al.*,
734 2023). For cell type annotations we used the cell type annotations: class (e.g., GABAergic
735 neurons) and subclass (e.g. SST^+ interneurons) for first and second level EWCE analysis,
736 respectively. Bootstrap enrichment tests were performed using 10,000 reps to look whether
737 gene sets (i.e., foreground) were significantly enriched for a cell class or subclass relative to
738 the background (i.e., all detected proteins included in that contrast). Since we focused on
739 neuronally-enriched proteins or SYNGO-annotated synaptic proteins, we excluded non-
740 neuronal enrichment scores.

741 EWCE calculates cell type-specificity scores (CTSS) for all genes, which is the
742 percentage of mean expression per cell type relative to the sum of the mean expressions of
743 all cell types. We used the CTSS to predict for each protein the cell type the protein probably
744 is derived from. We only included CTSS from genes that passed mRNA detection threshold
745 (mean expression >4 in at least one cell class). Cell type predictions included neuronal
746 (neuronal CTSS > 70%), GABAergic neurons (GABA CTSS > 0.8 and glutamatergic CTSS < 0.1),
747 glutamatergic neurons (glutamatergic CTSS > 0.8 and GABAergic CTSS < 0.1). Cell type
748 predictions were labelled in volcano plots. We also used the EWCE-calculated mean mRNA
749 expression for each cell type to estimate the differential expression of genes in GABAergic
750 vs glutamatergic neurons, which was used in the SYNGO manual colour plots (Figure 6H)).

751 *Heatmaps and line plots*

752 We used the mean log_2-transformed normalized protein intensities per group (i.e., PBAD 4
753 WPI) and plotted these values using line plots in RStudio(Team, 2020) using ggplot(Wickham,

754 2016). The relative normalized protein intensities (log_2(FC)) was used in heatmaps, which
755 were produced using Morpheus. To map these proteins to predicted cell types we also show
756 EWCE-calculated cell type specificity scores. All heatmaps visualizations are with fixed colour
757 scaling (i.e., not relative colour scaling per gene), as indicated by heatmap legend.

758 *Gene-set enrichment analysis using GOAT and over-representation analysis using SYNGO*
759 We used the output of the differential abundance analysis using MSDAP (PB-AD 10 vs 4 WPI
760 and NGN2 10 vs 4 WPI) as input for gene-set enrichment analysis using GOAT. The GOAT
761 online v1.0.2(Koopmans, 2024b) was used to perform gene set enrichment analyses using
762 gene sets from the SynGO knowledgebase v1.2(Koopmans *et al.*, 2019b). Effect size-derived
763 gene scores (i.e., log_2(FC)) were used to test for enriched gene sets that contained at least 10
764 and at most 1500 genes (or 50% of the gene list, whichever was smaller) that overlapped
765 with the input gene list. Multiple testing correction was independently applied per gene set
766 "source" (i.e. SYNGO_CC, SYNGO_BP) using Bonferroni adjustment and all p-values were again
767 adjusted using Bonferroni correction to account for 2 separate tests across "sources". The
768 significance threshold for adjusted p-values was set to 0.05. SYNGO over-representation
769 analysis was performed using the same MSDAP output. Foreground was defined as
770 upregulated proteins per contrast (p-adjusted < 0.05 and log_2(FC) > 0.1), and the background
771 contained all tested genes for that contrast. SynGO release is dataset version: 20231201, and
772 default settings were used. Ontologies are significantly enriched at 1% FDR, while including
773 terms containing at least three matching input genes.

774 *Material availability*
775 PiggyBac *Ascl1-Dlx2* construct is available from Addgene #182307. The mass spectrometry
776 proteomics data have been deposited to the ProteomeXchange Consortium via the PRIDE
777 partner repository(Perez-Riverol *et al*, 2025) with the dataset identifier PXD064163.
778

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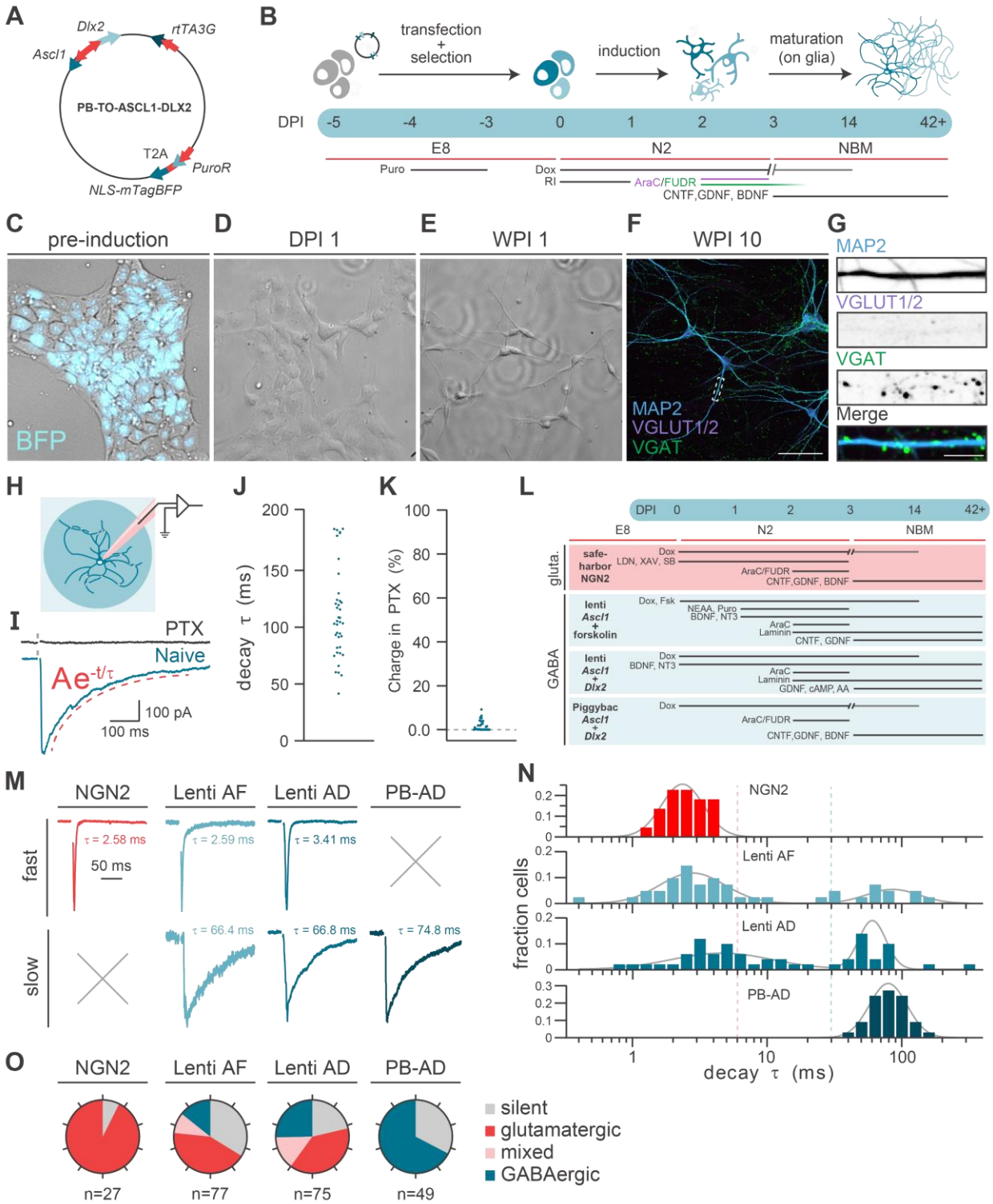

Figure 1. PiggyBac Asc1/Dlx2 efficiently generates pure GABAergic neurons,

A Map of the all-in-one PiggyBac (PB) vector, expressing murine *Ascl1* and *Dlx2* from a bi-directional TRE-responsive promoter, rtTA from the CAG promoter and *pac*-T2A-NLS-mTagBFP from the EF1α promoter. **B** Overview of the protocol for *Ascl1/Dlx2* induction. **C**

Before induction, all iPSCs show nuclear BFP signals, demonstrating successful integration of the PB construct **D** Dox-induced expression of *Dlx2* and *Ascl1* triggers neuronal morphology to arise within one day (DPI1) **E** A week after induction (WPI 1), neural morphology is clearly visible **F** After 10 weeks of culture, PB *Ascl1/Dlx2* induced neurons show mature neuronal morphology with GABAergic synapses (VGAT+ puncta) and no glutamatergic synapses (VGLUT+ puncta) Scale bar: 100 µm **G.** Zoom-in on the dendrite highlighted in F. scale bar = 1 µm. **H** Autaptic cultures of PB *Ascl1/Dlx2* induced neurons were assessed using patch clamp electrophysiology. **I** Evoked postsynaptic currents (PSCs) were fitted using a mono-exponential decay function (red) and their currents were diminished by the application of PTX. **J** Dot-plot of the decay time constants of ePSCs recorded in PB *Ascl1/Dlx2* induced neurons. **K** Dot-plot showing the distribution of cells with 0-10% of the naïve charge remaining in PTX **L** Overview of the four induction methods used, PB *Ascl1/Dlx2* induction was compared to the lentiviral *Ascl1/Dlx2* induction, *Ascl1*+Forskolin induction and *NGN2* glutamatergic induction. **M** Example ePSC traces with either fast or slow decay, as measured in the inductions tested here. **N** Histogram of log-transformed decay time constants (decay τ) measured in neurons induced with the four different induction strategies, together with a 'sum of two gaussians' fit (grey line). **O** Pie-charts showing the percentages of neurons with a slow ($\tau \geqslant 30$ ms), intermediate ($6 > \tau < 30$ ms) and fast ($\tau \leqslant 6$ ms) decay, as well as the percentage of synaptically silent neurons, of neurons generated with the four different induction strategies.

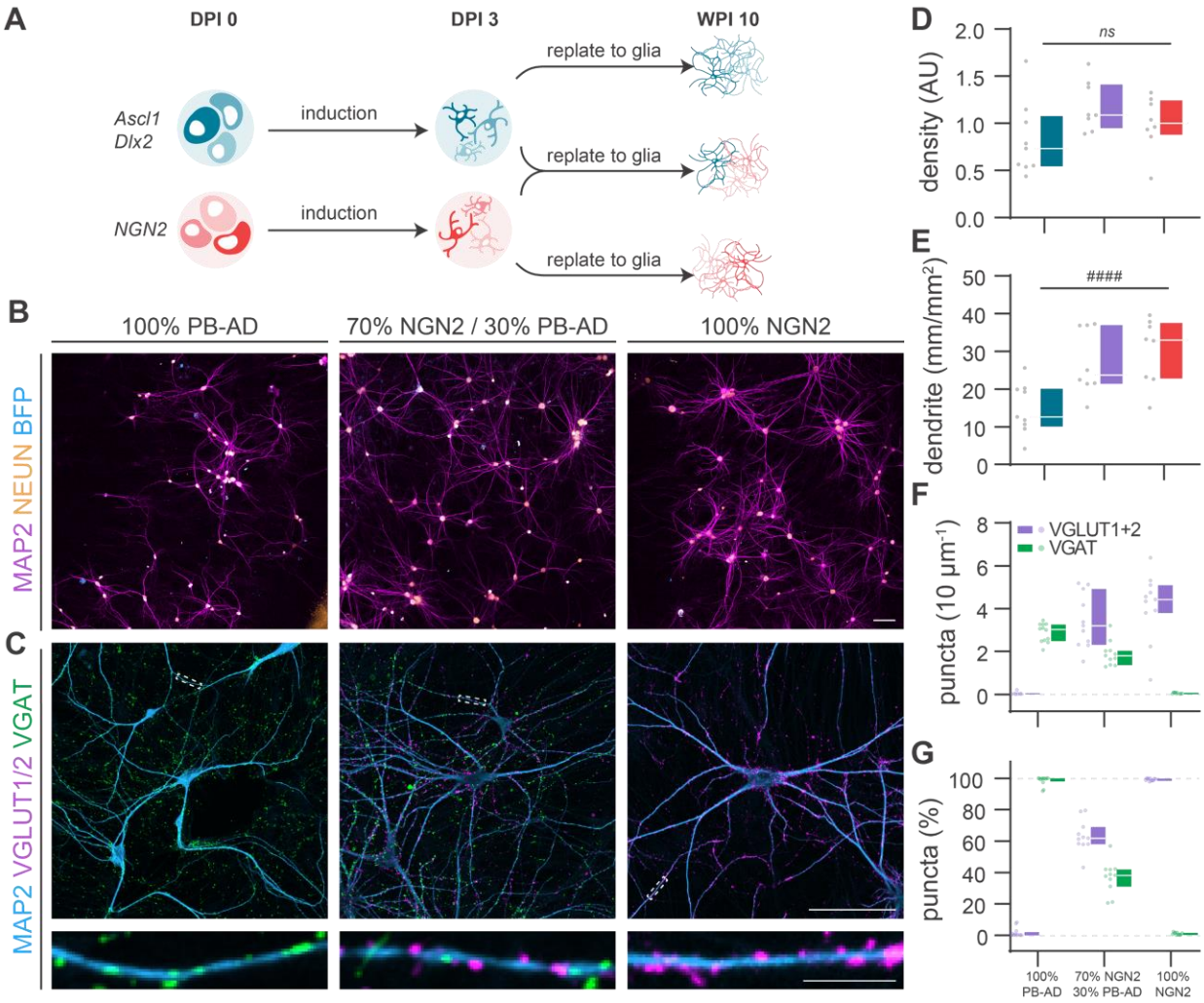

Figure 2. PiggyBac Ascl1/Dlx2 neurons integrate into well-defined excitatory/inhibitory networks upon co-culturing with NGN2 induced neurons

A Schematic of co-culturing protocol in which PiggyBac (PB) Ascl1/Dlx2 (AD) neurons were co-cultured with glutamatergic NGN2 induced neurons to generate excitatory/inhibitory (E/I) co-cultures **B** Representative images of E/I co-cultures at different ratios in which dendrites and neuronal nuclei are visualised using MAP2 and NeuN staining, respectively, and PB-AD neurons visualised by nuclear mTagBFP signals. The E/I-ratio is indicated above each image. Scale bar = 100 µm. **C** Representative images of E/I co-cultures at the same ratios as depicted in (B), stained for MAP2 as dendritic marker and VGAT and VGLUT as markers for GABAergic and glutamatergic synapses, respectively. Scale bars = 100 µm, scale bar zoom in = 10 µm **D** The network density (number of nuclei/field of view) is stable across E/I co-culture ratios. **E** The total dendrite length per field of view decreases as the percentage of plated PB-AD

1255 neurons increases. **F** The density of glutamatergic (VGLUT^{+} puncta) and GABAergic (VGAT^{+})
1256 puncta scales with the percentage of NGN2 and PB-AD neurons plated. **G** Synapse counts
1257 shown in F expressed as the percentage of all synapses counted.
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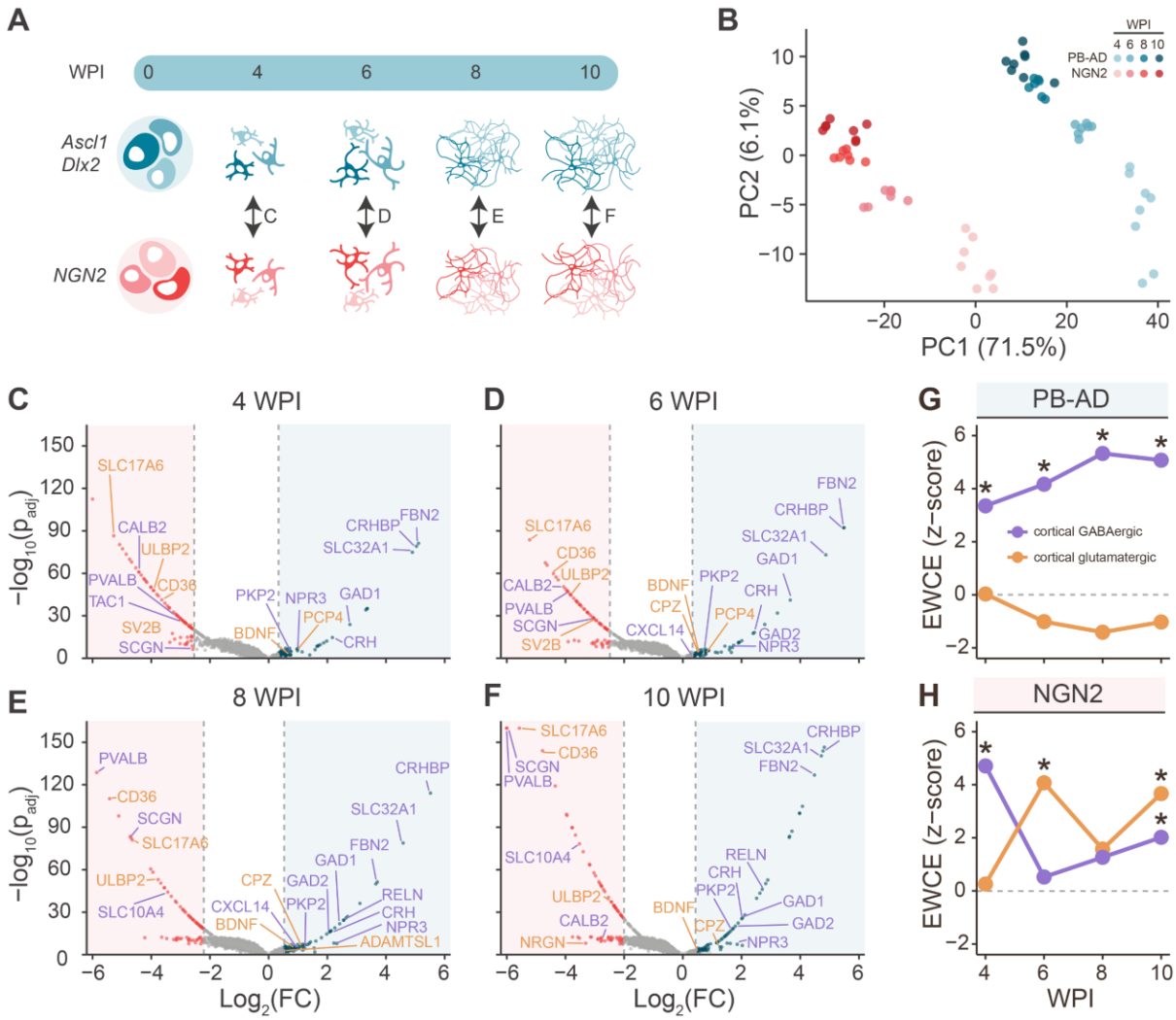

Figure 3. PiggyBac *Ascl1/Dlx2* neurons have a cortical GABAergic proteomic profile. **A**. Schematic overview of the proteomics analysis in which PiggyBac (PB) Ascl1/Dlx2 (AD) rat astrocyte co-cultures were compared to NGN2 co-cultures per timepoint. Double-sided arrows indicate the contrasts used for analysis. **B**. PCA analysis on neuronal protein abundances reveals separation of culture types as well as time points along the first two components (PC1: 61.7% and PC2: 8.0%). **C-F**. Volcano plots showing regulation of neuronal proteins in PB-AD cultures and in NGN2 cultures at 4 WPI (**C**), 6 WPI (**D**), 8 WPI (**E**) and 10 WPI (**F**). The top 5% significantly upregulated neuronal proteins in PB-AD are shown as blue dots and those in NGN2 as red dots. Proteins are considered significantly regulated if their adjusted p-value is < 0.05 (significance threshold overlaps with x-axis at this scale and is not shown for clarity of the figure) and their $\log_2$(FC) lies above the 95th or below the 5th percentile (vertical dashed lines). Label colours indicate the predicted cell types based on

1273 cell type specificity scores (CTSS): regulated GABAergic (purple) and glutamatergic proteins
1274 (orange). Cell type specificity was defined using the following CTSS cutoffs: neuronal proteins
1275 (neuronal CTSS>70%), GABAergic proteins (GABAergic CTSS > 80% and glutamatergic CTSS
1276 < 10%), glutamatergic proteins (glutamatergic CTSS > 80% and GABAergic CTSS < 10%). CTSS
1277 can be found in Figure S6. **G**. EWCE analysis of top 5% upregulated neuronal proteins in PB-
1278 AD cultures reveals specific enrichment for GABAergic neurons, which increased up to 8 WPI.
1279 **H**. EWCE analysis of the top 5% upregulated neuronal proteins in NGN2 cultures reveals
1280 significant enrichment for both glutamatergic and GABAergic neurons depending on the
1281 timepoint.
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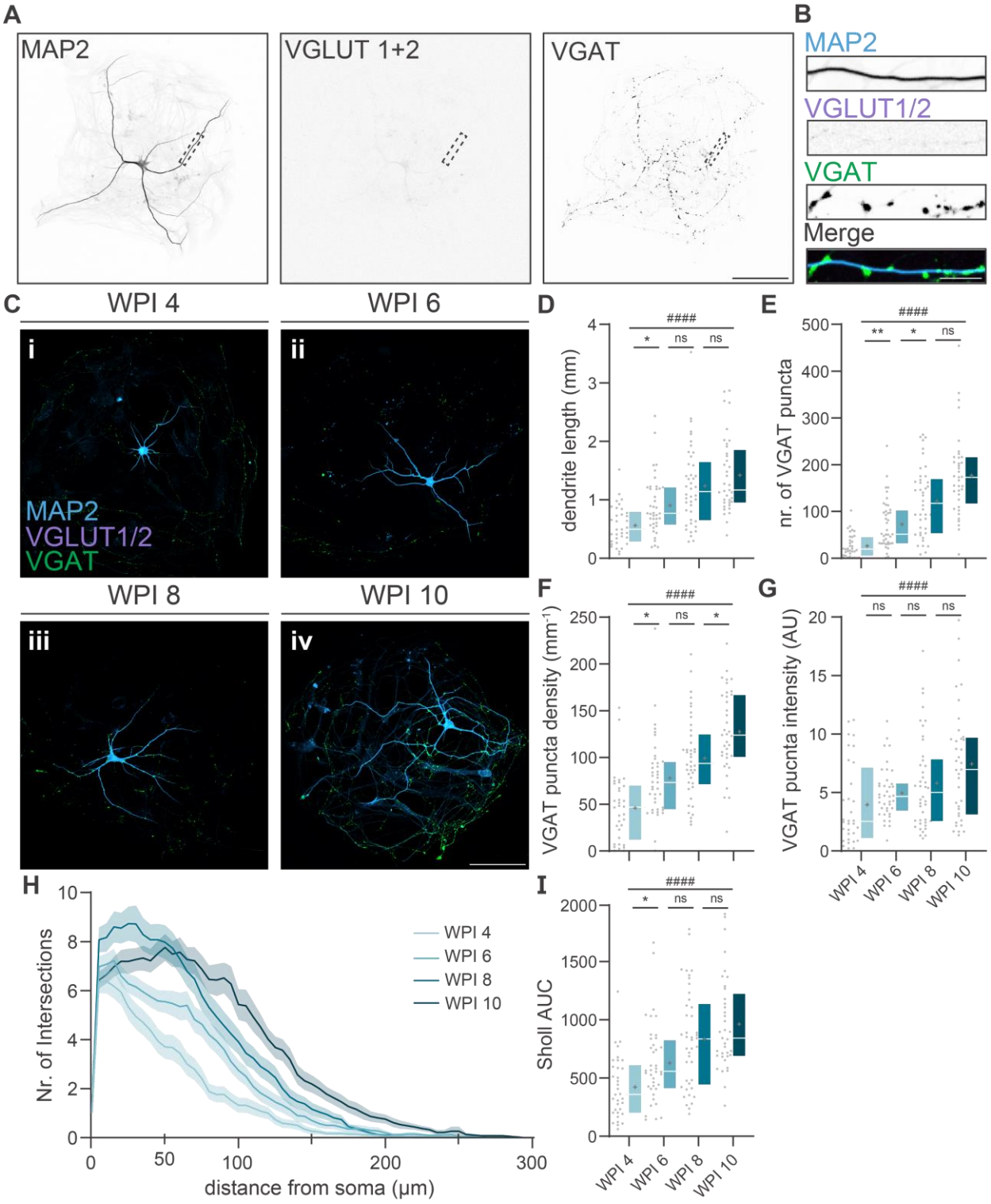

Figure 4. Morphological development of PiggyBac Ascl1/Dlx2 induced neurons

A Representative images of an autaptic PiggyBac (PB) *Ascl1/Dlx2* (AD) induced neuron at week-post-induction 10, stained for MAP2 as dendritic marker, and VGAT and VGLUT1/2 as

GABAergic and glutamatergic markers, respectively. Scale bar: 100 μm **B** Cut-out of dendrite marked in A to illustrate individual synaptic puncta. Scale bar: 10 μm **C** Typical examples of PB-AD autaptic neurons at WPI 4(i), 6(ii), 8(iii) and 10(iv). Scale bar: 100 μm **D** Total dendrite length quantified. **E** number of GABAergic synapses per neuron. **F** Synaptic density. **G** Average VGAT puncta intensity in arbitrary units (AU). Scale bars: 100 μm. Boxplot whiskers extend the entire data range. **H** Sholl analysis of PB-AD autaptic neurons at WPI 4, 6, 8 and 10. Shaded areas represent the SEM. **I** Quantification of the area under the curve (AUC) of the Sholl histogram shown in (**H**).

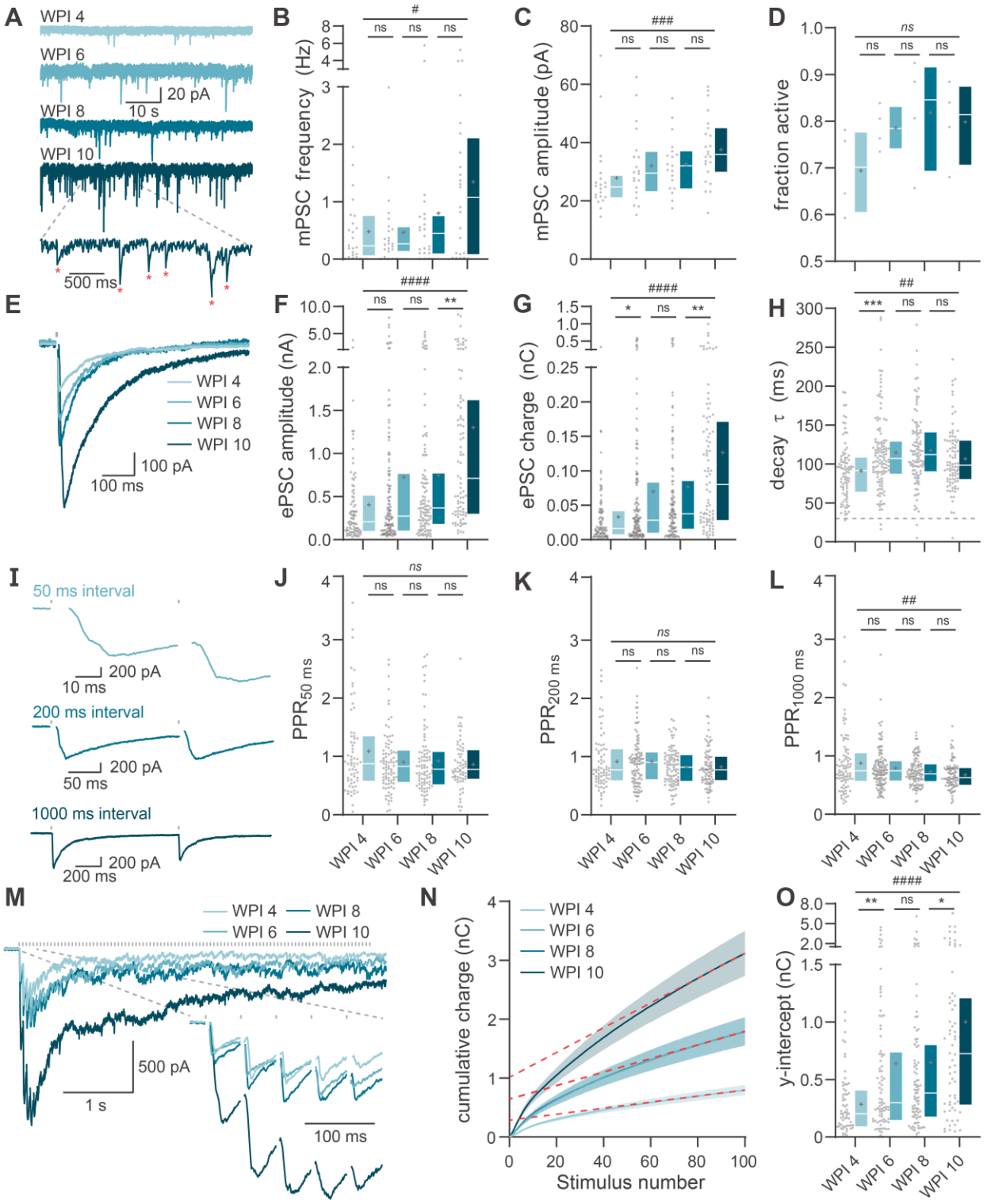

Figure 5. Functional development of PiggyBac Ascl1/Dlx2 induced neurons

A Representative traces of mPSCs recorded from PiggyBac (PB) *Ascl1/Dlx2* (*AD*) neurons (PB-AD) neurons at 4, 6, 8 and 10 weeks post induction (WPI). **B** mPSC frequency and **(C)**

amplitude of PB-AD neurons at 4, 6, 8 and 10 WPI. **D** Boxplots of the average fractions of synaptically active cells at 4, 6, 8 and 10 WPI. Markers represent averages of individual inductions. **E** Representative ePSC traces of at 4, 6, 8 and 10 WPI. **F** Amplitude charge (**G)** and decay time (**H**) constant of ePSCs recorded from PB-AD neurons at 4, 6, 8 and 10 WPI. **I** Representative traces of paired-pulse ePSCs at a 50, 200 and 1000 ms interval at 10 WPI. **J** Quantified paired-pulse amplitude ratios (PPR) at a 50 ms, 200 ms (**K**) and 100 ms (**L**) interval at 4, 6, 8 and 10 WPI. **M** Representative traces of iPSCs evoked by 20Hz stimulus trains from PB-AD neurons at 4, 6, 8 and 10 WPI with zoom in on first five pulses. **N** Plot of cumulative iPSC charge evoked by 20 Hz stimulus trains, with back-extrapolated linear fits displayed in red. Note, WPI 4 and WPI 6 data overlap. **O** RRP estimate obtained from back-extrapolation of linear fits displayed in N.

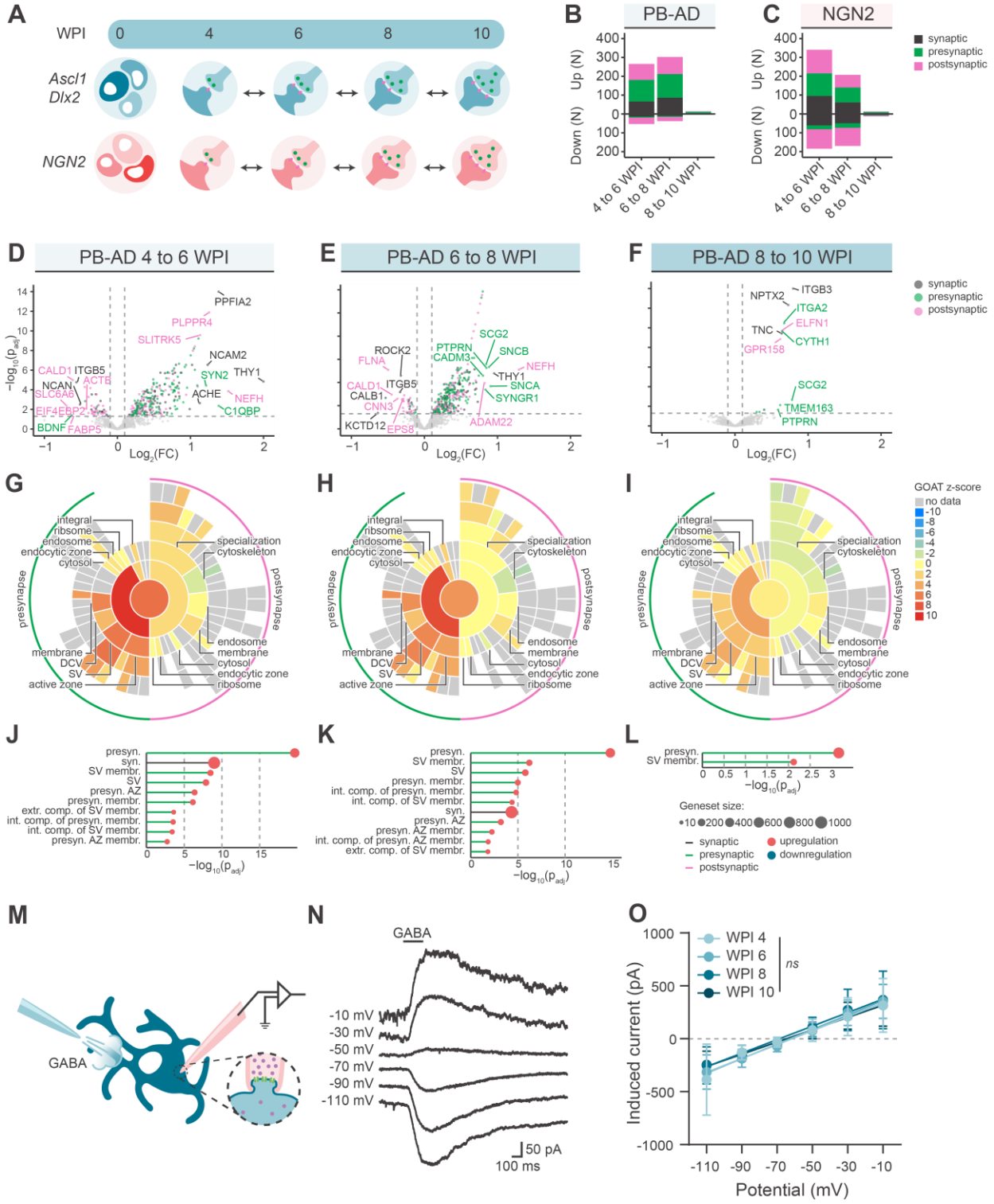

Figure 6. Pre- and postsynaptic maturation of PiggyBac Ascl1/Dlx2 neurons

A. Schematic overview of the proteomics analysis with double-sided arrows indicating the contrasts used for analysis. **B-C**. Stacked bar plots showing the number of up- and

downregulated SYNGO annotated proteins over time, distinguishing synaptic (black), exclusively presynaptic (green) and exclusively postsynaptic (magenta) proteins for PB-AD (**B**) and NGN2 (**C**) neurons. Classifications were assigned based on SynGO annotations, synaptic classification contains both pansynaptic and ambiguously localized synaptic proteins. Regulated proteins have a $\log_2(FC) > 0.1$, or < -0.1, and adjusted p-value < 0.05. **D-F.** Volcano plots showing regulation of synaptic proteins between 6 and 4 (**D**), 8 and 6 (**E**), and 10 and 8 WPI (**F**). Only SYNGO-annotated proteins are plotted and colour coding refer to significantly regulated synaptic (black) exclusively presynaptic (green) or postsynaptic (pink) annotations. Proteins were regarded significantly regulated when adjusted p-value < 0.05 (dashed horizontal line) and $\log_2(FC) > 0.1$ or < -0.1 (dashed vertical lines). Top 5% proteins regulated proteins were labelled based on 97.5^{th} and 2.5^{th} percentiles marking genes that drive subsequently detected enrichments. **G-I**. SYNGO plots showing enrichment scores (z-scores) derived from gene-set enrichment analysis with GOAT on SYNGO cellular compartment gene sets, using differential expression output of 6 vs 4 (G), 8 vs 6 (H) and 10 vs 8 WPI (I),. Negative z-scores reflect enrichments primarily driven by downregulated proteins and vice versa for positive z-scores. **J-L.** Lollipop charts showing significant ontologies with their corresponding adjusted p-values and the number of genes part of the gene set as analysed by GOAT for 6 vs 4 (J), 8 vs 6 (K) and 8 vs 10 WPI (L) **M.** Schematic overview of the GABA puff experiment, in which perforated-patch was performed on PB-AD neurons in E/I-networks and GABA was applied to measure the postsynaptic current it produced. **N.** Typical example of the postsynaptic current produced by GABA puff at different holding voltages. **O.** Linear fit of PSC amplitudes as measured in response to GABA puff at 4, 6, 8 and 10 WPI. Error bars represent the SD.

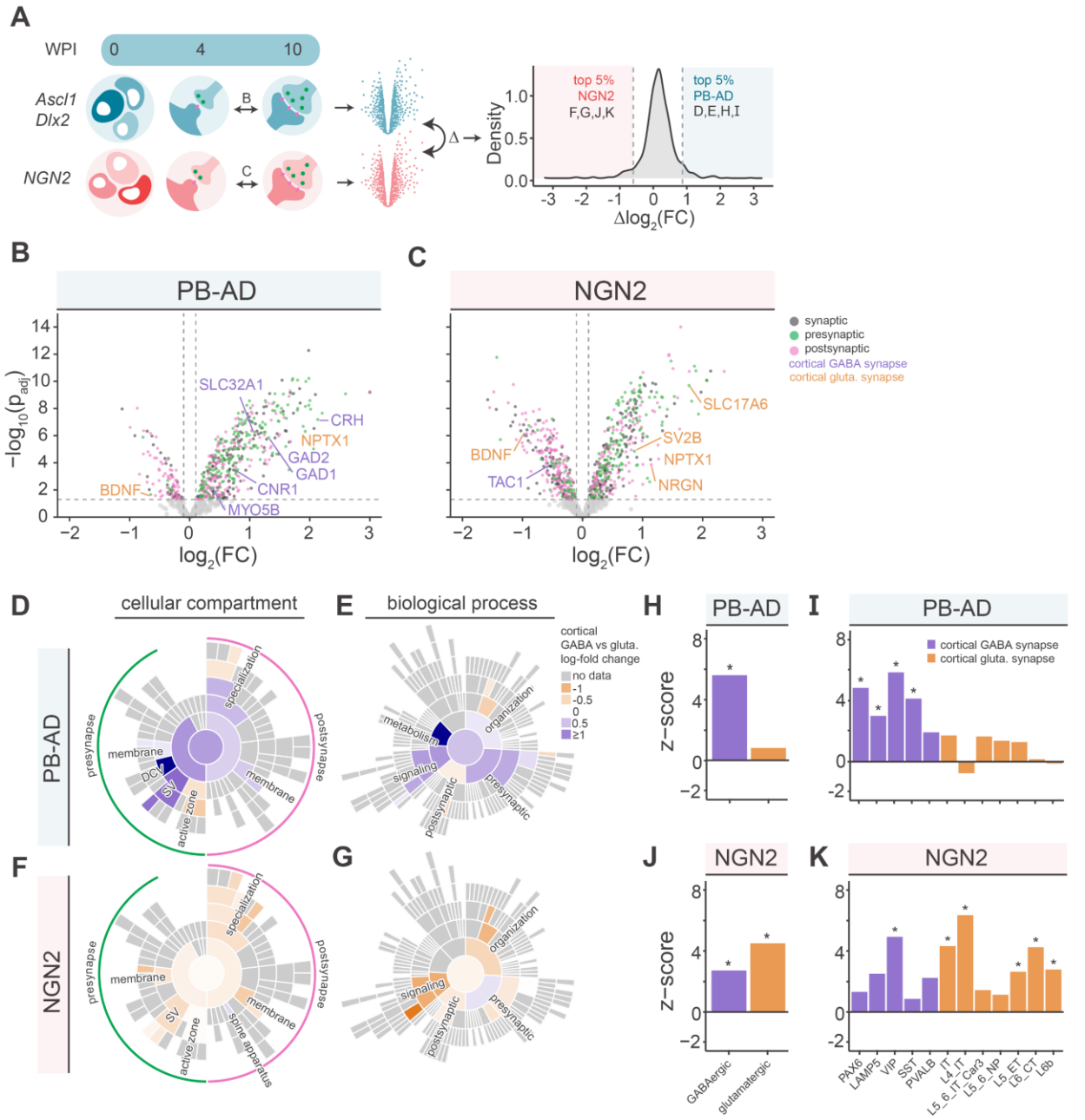

Figure 7. Specialization of PiggyBac Ascl1/Dlx2 and NGN2 neurons into cortical subtypes

A. Schematic overview of the proteomics analysis pipeline. The differential expression of synaptic proteins over time (10 vs 4 WPI) was first quantified for PB-AD and NGN2 culture separately. The difference in expression over time between PB-AD and NGN2 (delta- $\log_2$(FC)) was next calculated, enabling identification of proteins with PB-AD- or NGN2-specific temporal profiles. Density plot showing 5th and 95th percentiles (dashed vertical lines) selections of proteins that have strong differential temporal regulation (i.e., high or low

delta- log_2(FC)) in PB-AD compared to NGN2, and vice versa. **B-C**. Volcano plots showing regulation of synaptic proteins between 10 and 4 WPI. Proteins are considered regulated when the log_2(FC) > 0.1 or < -0.1 (dashed vertical lines) and adjusted p-value < 0.05 (dashed horizontal line). Only SYNGO-annotated proteins are plotted, and dot colors refer to significantly regulated synaptic (black) exclusively presynaptic (green) or postsynaptic (pink) annotations. Label colours indicate for predicted cortical GABAergic- (purple) or glutamatergic (orange) regulated proteins. **D-G** SYNGO sunburst plots showing the GABAergic and glutamatergic specification of PB-AD and NGN cultures. The SYNGO sunburst inputs are the proteins that are part of the 5th (**F-G**) and 95th percentiles (**D-E**) from the delta-log_2(FC) distribution (**A**), which represent the top 5% exclusively PB-AD and NGN2 regulated proteins, respectively. GABAergic or glutamatergic annotation for these SYNGO terms is estimated based on the differential RNA expression (log_2(FC)) between cortical GABAergic and glutamatergic neurons of corresponding genes(Jorstad *et al.*, 2023). Both cellular compartment (**D-F**) and biological process (**E-G**) gene sets were used. **H-K**. EWCE analysis of PB-AD-specific (**H-I**) or NGN2-specific proteins (**J-K**) show enrichment for GABAergic and glutamatergic cell sub(classes), respectively. IT and ET refer to intra- and extratelenchephalic-projecting neurons and NP refers to near-projecting neurons(Jorstad *et al.*, 2023).

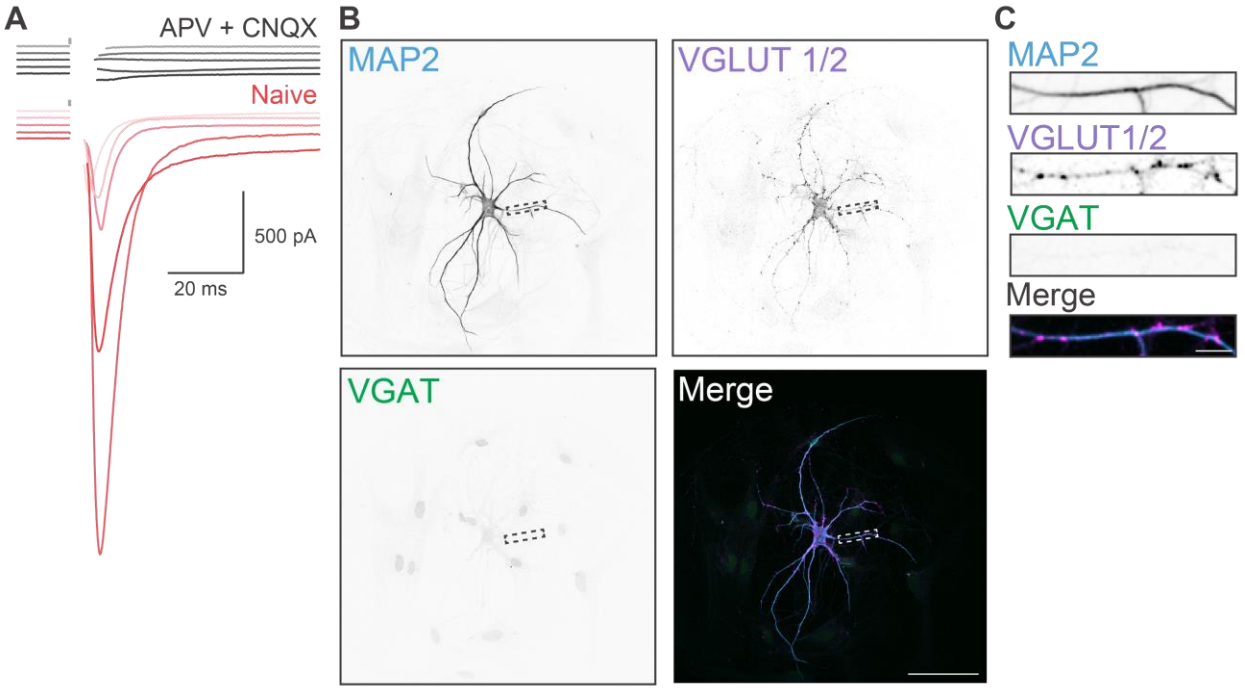

Figure S1. NGN2 neurons produce glutamatergic transmission

A Voltage clamp recordings of 6 WPI NGN2 autaptic neurons after stimulation, in normal ACSF (Naive) and in presence of glutamatergic receptor blockers (APV + CNQX). Synaptic transmission was fully abolished by blockers, illustrating that NGN2 neurons are glutamatergic. **B-C** Examples of immunocytochemistry for MAP2, VGAT and VGLUT1+2 performed on NGN2 autaptic neurons, with zoom in on a length of dendrite (**C**). Scale bar = 100 µm, zoom in scale bar = 10 µm

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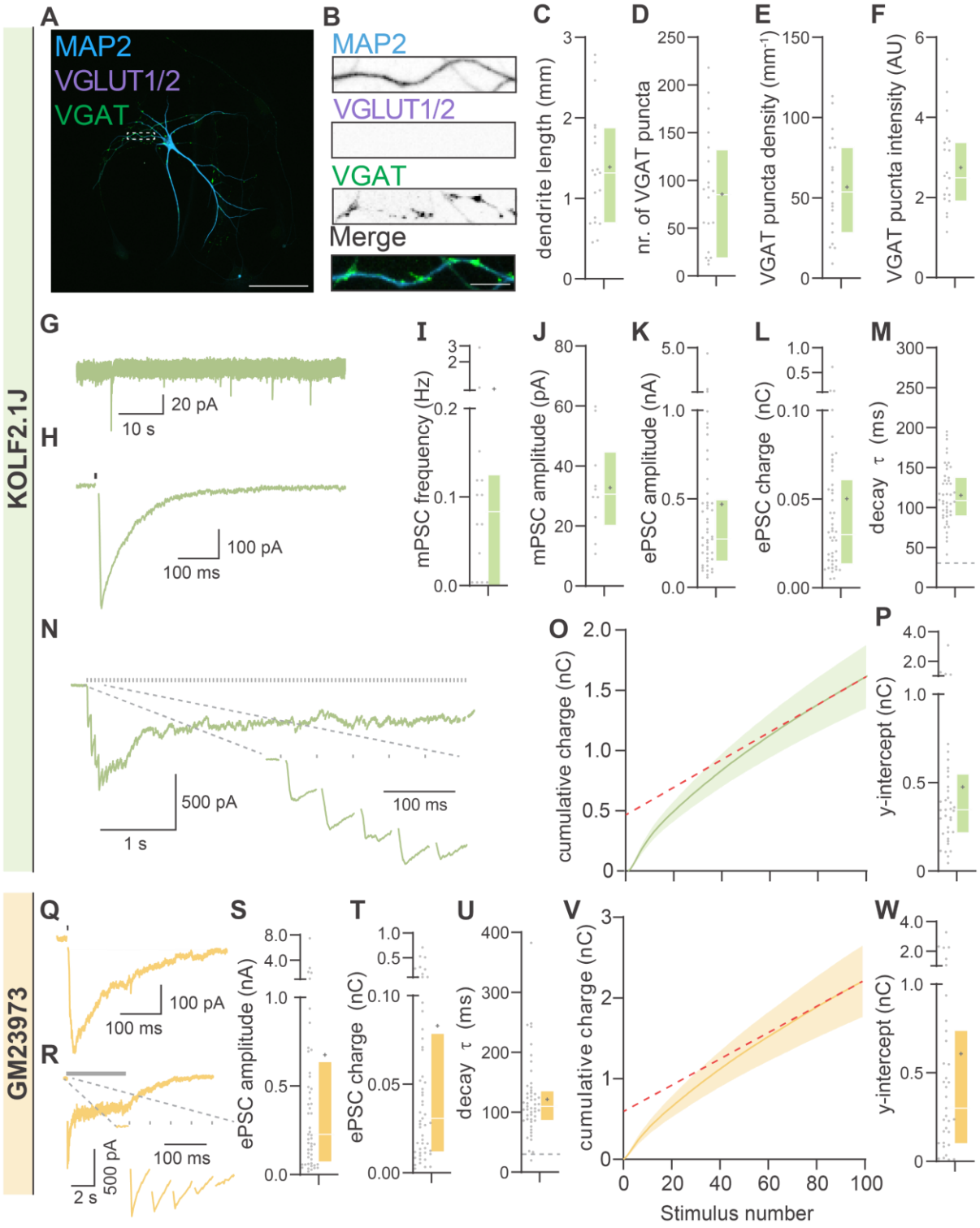

KOLF2.1J
GM23973
A
MAP2
VGLUT1/2
VGAT
B
MAP2
VGLUT1/2
VGAT
Merge
C
dendrite length (mm)
D
nr. of VGAT puncta
E
VGAT puncta density (mm⁻¹)
F
VGAT pucnta intensity (AU)
G
20 pA
10 s
H
100 pA
100 ms
I
mPSC frequency (Hz)
J
mPSC amplitude (pA)
K
ePSC amplitude (nA)
L
ePSC charge (nC)
M
decay τ (ms)
N
500 pA
1 s
100 ms
O
cumulative charge (nC)
P
y-intercept (nC)
Q
100 pA
100 ms
R
500 pA
2 s
100 ms
S
ePSC amplitude (nA)
T
ePSC charge (nC)
U
decay τ (ms)
V
cumulative charge (nC)
Stimulus number
W
y-intercept (nC)

1386

1387 **Figure S2. PiggyBac Ascl1/Dlx2 induction reliably generates GABAergic neurons in the**
1388 **KOLF2.1J and GM23973 line**
1389 **A** Representative images of PiggyBac (PB) Ascl1/Dlx2 (AD) neurons induced from KOLF1.2J
1390 iPSCs at 7 weeks post induction (WPI), stained for MAP2 as dendritic marker, and VGAT and
1391 VGLUT1/2 as GABAergic and glutamatergic markers, respectively**.** Scale bar: 100 µm **B** Zoom-
1392 in on dendrite to illustrate punctate VGAT staining. Scale bar: 10 µm **C.** Total dendrite length
1393 and (**D**) number of GABAergic synapses per neuron. **E** Synaptic density and intensity (**F**). **G**
1394 Representative mPSC trace and (**H**) representative ePSC trace from PB-AD neurons induced
1395 from the KOLF2.1J line. **I** Frequency and (**J**) amplitude of miPSCs. **K** Amplitude, (**L**) charge and
1396 (**M**) decay time constant of iPSCs in PB-AD neurons generated from the KOLF2.1J line. **N**
1397 Representative trace of iPSCs evoked by 20Hz stimulation trains with zoom-in on first five
1398 pulses in KOLF2.1J. **O** Plot of cumulative iPSC amplitudes evoked by 20 Hz stimulus trains,
1399 with back-extrapolated linear fits displayed in red. **P** RRP estimate obtained from back-
1400 extrapolation of linear fits displayed in (**M**). **Q**. representative ePSC traces from PB-AD
1401 neurons induced from the GM23973 line. **R.** Representative trace of iPSCs evoked by 20Hz
1402 stimulation trains with zoom-in on first five pulses in GM23973. **S** Amplitude, (**T**) charge and
1403 (**U**) decay time constant of iPSCs in PB-AD neurons generated from the GM23973.1J line. **V**
1404 Plot of cumulative iPSC amplitudes evoked by 20 Hz stimulus trains, with back-extrapolated
1405 linear fits displayed in red. **W** RRP estimate obtained from back-extrapolation of linear fits
1406 displayed in (M). Boxplot whiskers extend the entire data range.
1407

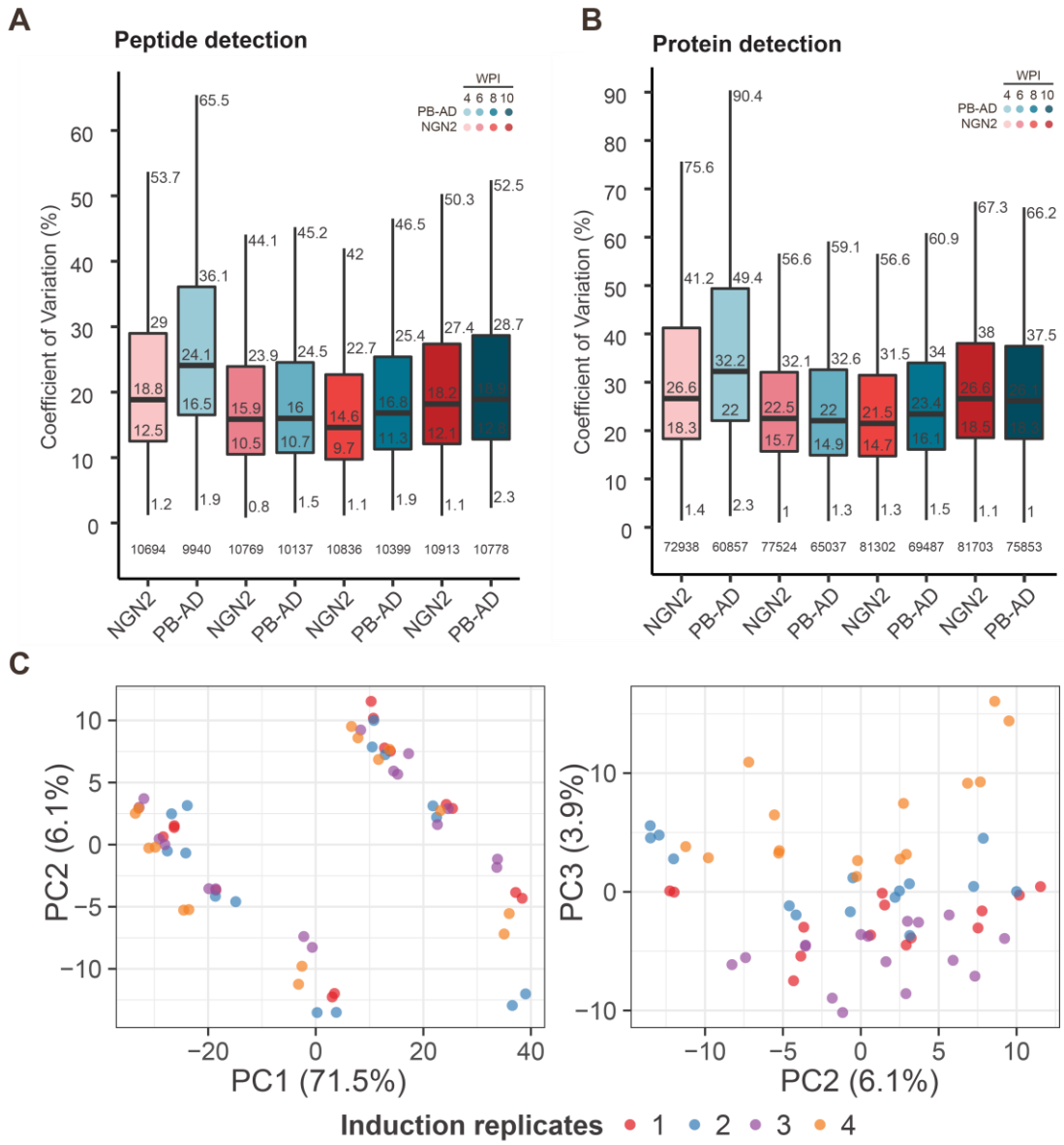


Figure S3. Peptide and protein detection count and variation is similar between cultures and timepoints.

A-B Boxplots showing variation of peptide (**A**) and protein (**B**) detection for all timepoints per culture, indicating median, 1st and 3rd quartiles, and minimum and maximum values. Number of detected peptides and proteins are indicated in the base of the graph. Median coefficient of variation for peptide and protein detection across groups ranged from 14.6% to 32.2%, reflecting consistent detection performance across replicates. **C** PCA plots showing potential batch effects due to induction. PC1 and PC2 show even spread of different inductions but PC3 (3.9%) shows slight separation based on induction and we therefore corrected for induction effect when performing differential abundance analysis.

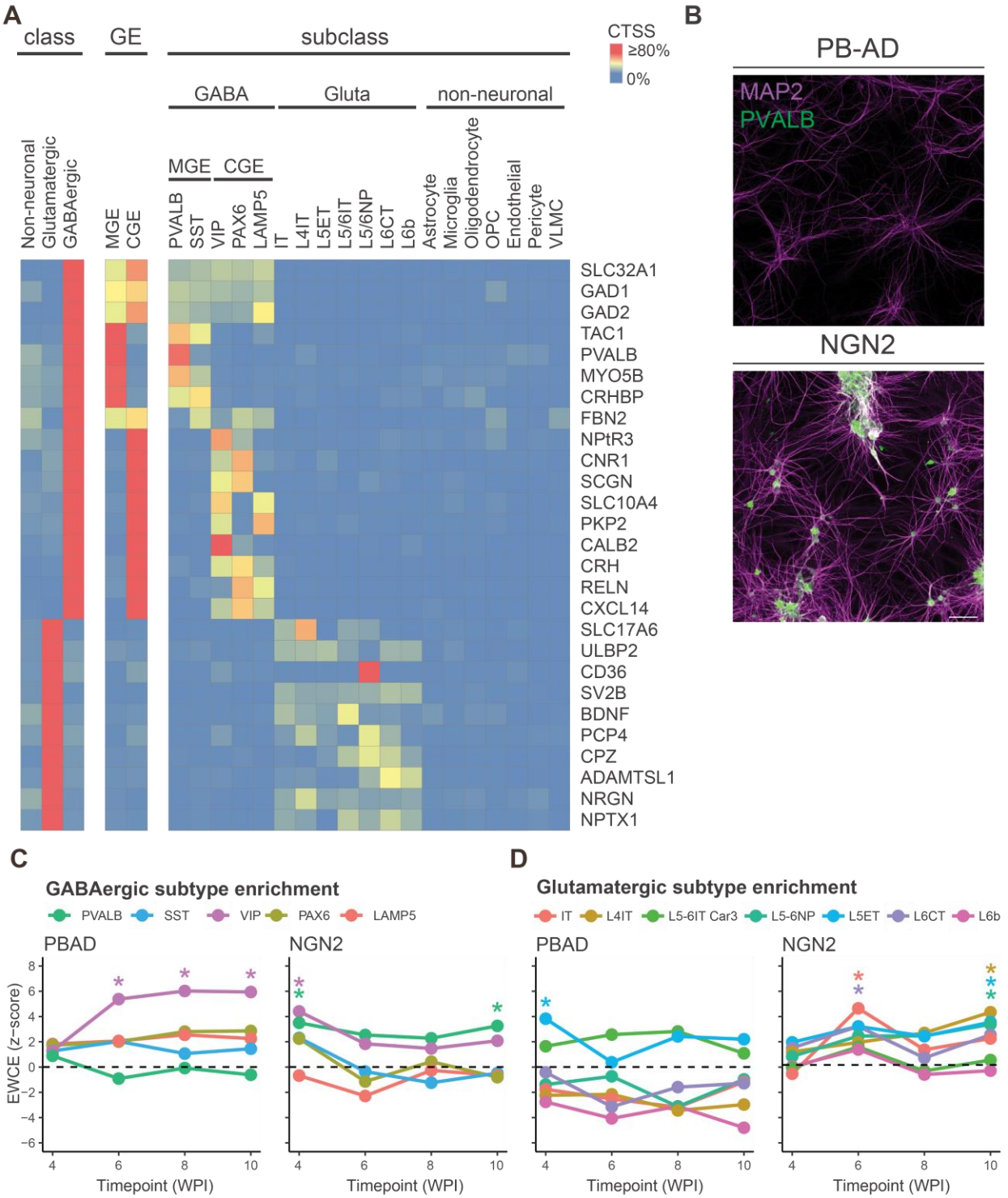
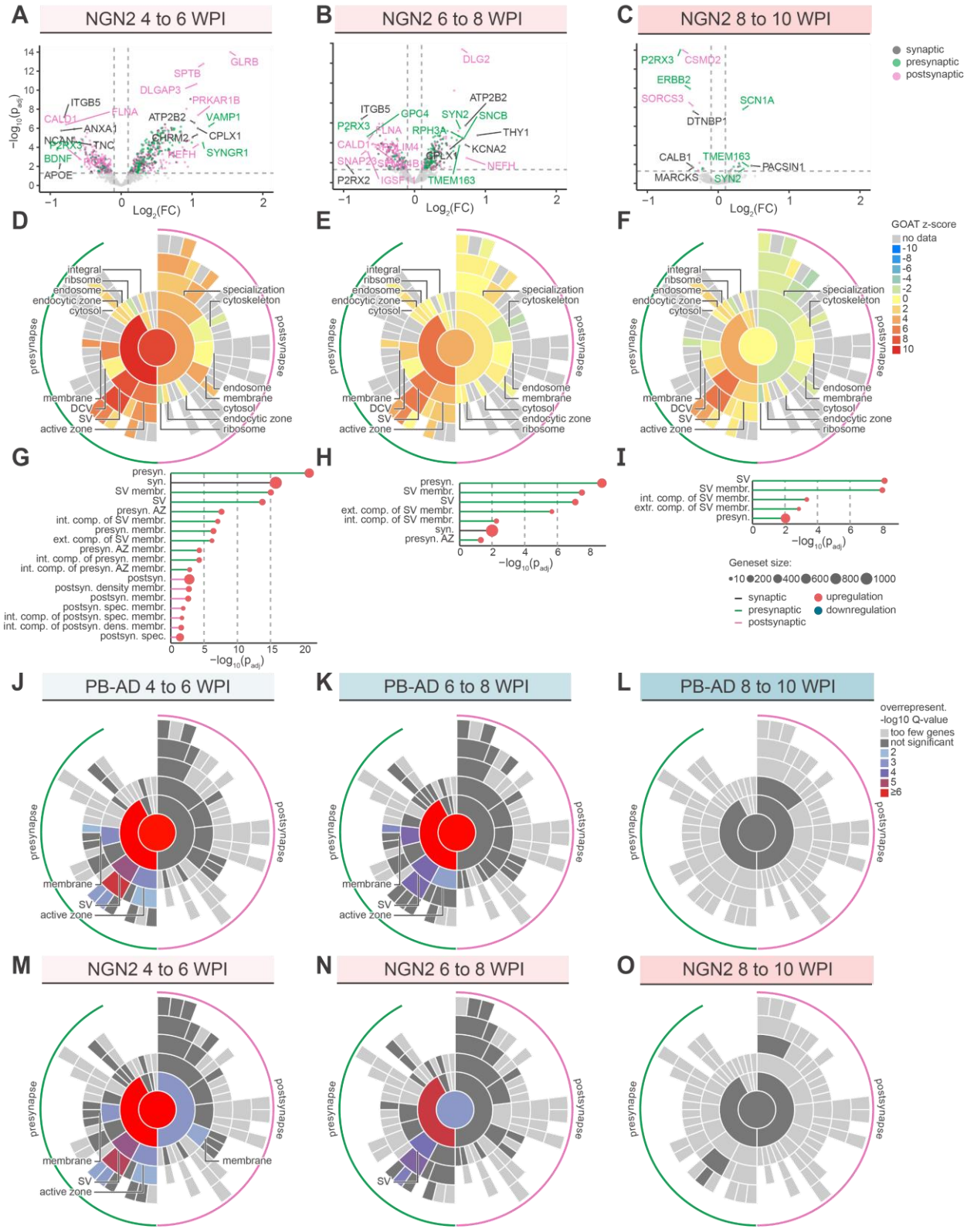


Figure S4. Cell type specificity scores for detected GABAergic proteins

A. Cell type specificity scores (CTSS) scores for detected GABAergic and glutamatergic proteins. CTSS are calculated with the expression weighted cell type enrichment tool (Skene

& Grant, 2016) using single-cell RNA-sequencing data from Jorstad et al. (Jorstad *et al.*, 2023). MGE and CGE refer to medial and caudal ganglionic eminences. **B.** Representative images of PB-AD and NGN2 neurons stained for MAP2 and PVALB. Scale bar = 100 µm. **C-D** Expression-weighted cell type enrichment (EWCE) analysis showing enrichment of proteins higher expressed in PB-AD or NGN2 for GABAergic **(C)** and glutamatergic subtypes **(D)**. PBAD-enriched proteins showed strongest enrichment for VIP^+ interneurons at most timepoints, whereas NGN2-enriched proteins map at different timepoints to both GABAergic ($PVALB^+$ and VIP^+ interneurons) and glutamatergic subtypes. PB-AD-enriched proteins showed unexpected enrichment for L5ET neurons at 4 WPI, which reduced below significance threshold at later timepoints. IT and ET refer to intra- and extratelenchephalic-projecting neurons, and NP refers to near-projecting neurons – cell subclass annotations consistent with Jorstad et al. (2023)(Jorstad *et al.*, 2023).


A
NGN2 4 to 6 WPI
B
NGN2 6 to 8 WPI
C
NGN2 8 to 10 WPI
synaptic
presynaptic
postsynaptic
Log2(FC)
D
E
F
GOAT z-score
no data
presynapse
postsynapse
integral
ribsome
endosome
endocytic zone
cytosol
specialization
cytoskeleton
membrane
DCV
SV
active zone
ribosome
G
H
I
Geneset size:
synaptic
presynaptic
postsynaptic
upregulation
downregulation
J
PB-AD 4 to 6 WPI
K
PB-AD 6 to 8 WPI
L
PB-AD 8 to 10 WPI
overrepresent.
-log10 Q-value
too few genes
not significant
M
NGN2 4 to 6 WPI
N
NGN2 6 to 8 WPI
O
NGN2 8 to 10 WPI

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1437 **Figure S5. Differential expression of synaptic genes in NGN2 and PB-AD neurons**
1438 **A-C.** Volcano plots showing regulation of synaptic proteins in NGN2 cultures between 6 and
1439 4 (**A**), 8 and 6 (**B**), and 10 and 8 WPI (**C**). Only SYNGO-annotated proteins are plotted and
1440 colour coding refer to significantly regulated synaptic (black) exclusively presynaptic (green)
1441 or postsynaptic (pink) annotations. Proteins were regarded significantly regulated when
1442 adjusted p-value < 0.05 (dashed horizontal line) and $\log_2$(FC) > 0.1 or < -0.1 (dashed vertical
1443 lines). **D-F**. SYNGO plots showing enrichment scores (z-scores) derived from gene-set
1444 enrichment analysis with GOAT using SYNGO cellular compartment gene sets for 4 to 6 (**D**),
1445 6 to 8 (**E**) and 8 to 10 WPI (**F**). Negative z-scores (blue) reflect enrichments primarily driven
1446 by downregulated proteins and vice versa for positive z-scores (red). **G-I.** Lollipop charts
1447 showing significant SYNGO terms with their corresponding adjusted p-values and the
1448 number of genes part of the gene set. **J-O.** SYNGO overrepresentation analysis of upregulated
1449 proteins in PB-AD (**J-L**) and NGN2 (**M-O**) per timepoint. Foreground are significantly
1450 upregulated proteins and background are all tested genes in corresponding contrast.

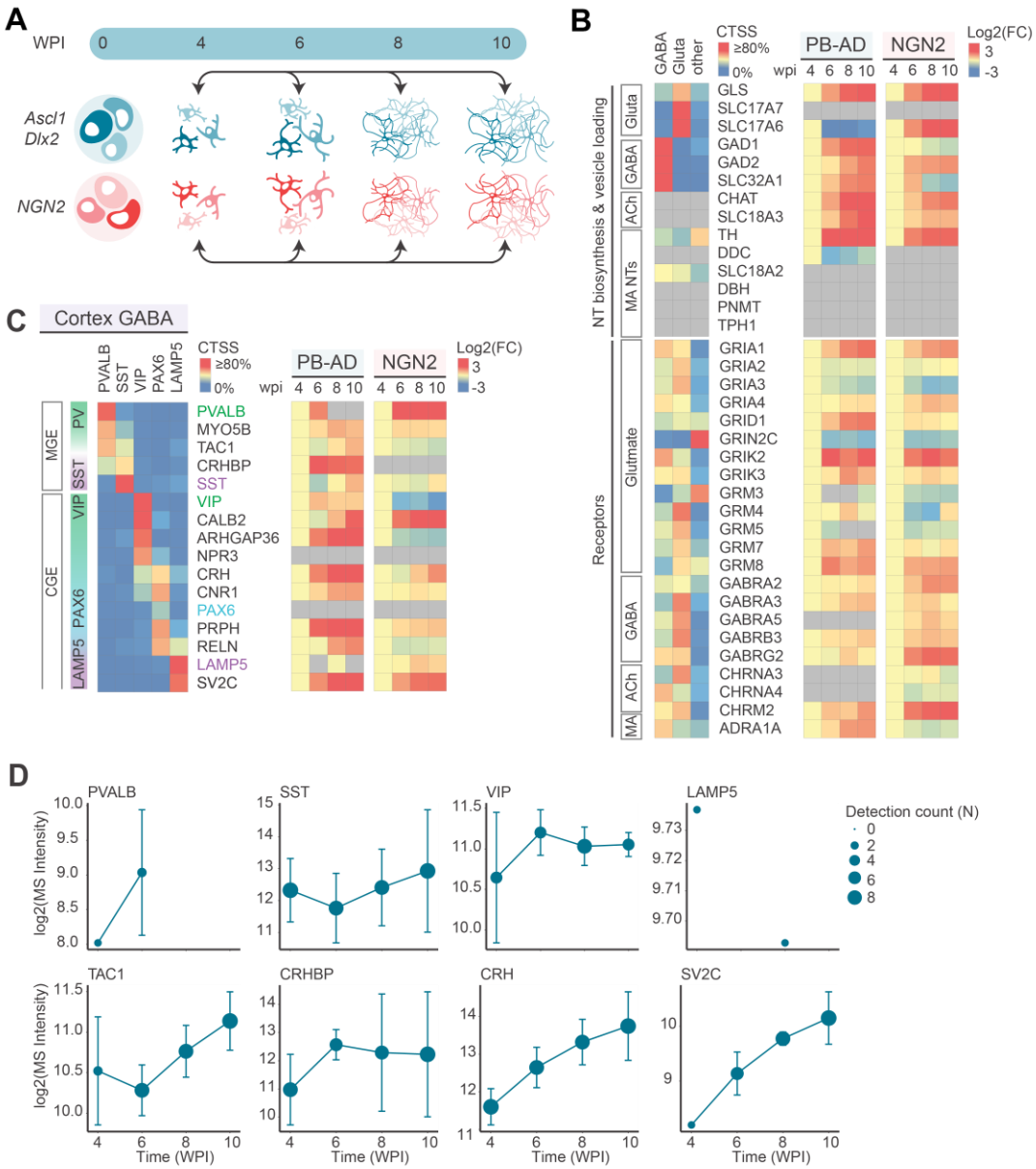

Figure S6. PiggyBac Ascl1/Dlx2 and NGN2 neurons express markers of diverse GABAergic neuron subtypes

A. Contrasts used to determine cell type specification. **B** and **C** Heatmaps that show temporal expression profiles relative to 4 WPI (log_2(FC)) and cell type specificity scores (CTSS). **B** Typical proteins required for neurotransmitter (NT) synthesis, vesicle loading, and receptors. Undetected proteins are visualized for NT biosynthesis and vesicle loading but not for receptors. **C** Canonical GABAergic subtype markers and proteins with high cell type specificity for GABAergic subtypes and for medial or caudal ganglionic eminences (MGE or CGE). **D.** Line plots show mean expression of canonical GABAergic subtype markers (top) and other

proteins with GABAergic cell type specificity. Error bars represent SD and dot size indicate detection count.

1464 **Supplemental table 1: SYNGO Proteins with significant expression changes from 8 to 10 WPI**
1465 **in PB-AD neurons**

Protein	new at WPI 10	log_2fc	FDR-adjusted p-value
CNTNAP4	yes	1.05	1.50E-26
SLITRK1	yes	0.97	7.75E-23
CDH1	yes	0.91	4.81E-20
EPHA7	yes	0.90	1.26E-19
ITGB3	no	0.80	1.72E-15
PRRT1	yes	0.74	1.35E-13
NPTX2	no	0.73	4.68E-13
ITGA2	no	0.67	3.46E-11
SLC17A5	yes	0.67	5.09E-11
KCNQ2	yes	0.65	1.77E-10
ELFN1	no	0.65	2.09E-10
CYTH1	no	0.65	2.21E-10
TNC	no	0.64	3.74E-10
NRGN	yes	0.63	6.71E-10
NGDN	yes	0.63	6.73E-10
GPR158	no	0.62	1.43E-09
RELN	yes	0.57	3.53E-08
SCG2	no	0.78	2.18E-03
TMEM163	no	0.62	7.64E-03
PTPRN	no	0.59	2.24E-02
NEFH	no	0.40	2.24E-02
IGSF8	no	0.40	2.24E-02
CNTNAP1	no	0.34	3.78E-02
ATP2B4	no	0.30	3.78E-02

1466