Postnatal subventricular zone progenitors switch their fate to generate neurons with distinct synaptic input patterns

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ABSTRACT

New granule cell neurons (GCs) generated in the neonatal and adult subventricular zone (SVZ) have distinct patterns of input synapses in their dendritic domains. These synaptic input patterns determine the computations that the neurons eventually perform in the olfactory bulb. We observed that GCs generated earlier in postnatal life had acquired an ‘adult’ synaptic development only in one dendritic domain, and only later-born GCs showed an ‘adult’ synaptic development in both dendritic domains. It is unknown to what extent the distinct synaptic input patterns are already determined in SVZ progenitors and/or by the brain circuit into which neurons integrate. To distinguish these possibilities, we heterochronically transplanted retrovirally labeled SVZ progenitor cells. Once these transplanted progenitors, which mainly expressed Mash1, had differentiated into GCs, their glutamatergic input synapses were visualized by genetic tags. We observed that GCs derived from neonatal progenitors differentiating in the adult maintained their characteristic neonatal synapse densities. Grafting of adult SVZ progenitors to the neonate had a different outcome. These GCs formed synaptic densities that corresponded to neither adult nor neonatal patterns in two dendritic domains. In summary, progenitors in the neonatal and adult brain generate distinct GC populations and switch their fate to generate neurons with specific synaptic input patterns. Once they switch, adult progenitors require specific properties of the circuit to maintain their characteristic synaptic input patterns. Such determination of synaptic input patterns already at the progenitor-cell level may be exploited for brain repair to engineer neurons with defined wiring patterns.

KEY WORDS: Adult neurogenesis, Synaptic development, Fate determination, Subventricular zone, Rat

INTRODUCTION

New neurons are continuously added to the adult mammalian brain. The most abundantly adult-generated neurons are granule cells (GC) in the olfactory bulb (OB). GCs are generated in the subventricular zone (SVZ) and integrate both into the developing (neonatal) and adult OB (Lois and Alvarez-Buylla, 1994). They are axon-less interneurons with an apical and a basal dendrite (Mori, 1987; Kelsch et al., 2010). The apical dendrite contains two domains (Fig. 1A). The proximal domain is an initial segment of the unbranched apical dendrite that receives axodendritic glutamatergic input synapses similar to the basal dendrite (basal domain). The distal domain starts after the first branch point of the apical dendrite. In the distal domain, GCs form reciprocal synapses with OB’ projection neurons that contain functionally coupled glutamatergic input and GABAergic output synapses (Hinds and Hinds, 1976).

Adult-born GCs differ in several features from neonatal-born GCs. Adult-born GCs acquire first synapses in the proximal domain and later in the distal domain (Whitman and Greer, 2007; Kelsch et al., 2008; Bardy et al., 2010). By contrast, neonatal-born neurons acquire synapses simultaneously in the proximal and distal domain (Kelsch et al., 2008). Adult-born GCs reach higher densities of glutamatergic synapses in the proximal domain than do neonatal-born neurons (Kelsch et al., 2008; Panzanelli et al., 2009). Neonatal- and adult-born neurons also respond differently to sensory deprivation (Kelsch et al., 2012), have different survival rates (Lemasson et al., 2005), and neonatal- but not adult-born neurons have slow presynaptic inhibition (Valley et al., 2013). Differences in the number of synaptic inputs in the dendritic domains determine the computations that GCs will eventually perform in the circuit (Lepouezes et al., 2013). For example, the number of synapses in the distal domain influences the number of OB’ projection neurons to which the GC provides recurrent inhibition. By contrast, glutamatergic inputs to the proximal domain emerge from the olfactory cortices and modulate GC inhibition during olfactory processing (Yokoyama et al., 2011; Soria-Gómez et al., 2014). We therefore examined the domain-specific synaptic densities that GCs form at the end of their maturation.

Recent studies have revealed an unexpected degree of diversity in the intrinsic programs that determine neurotransmitter fate and cell type-specific connectivity of neurons derived from adult stem cells (Rakic et al., 2009; Ming and Song, 2011; Weinandy et al., 2011). It is an unanswered question whether GCs adopt the synaptic input patterns typical of the host circuit in which they integrate. Or, the differences in the synaptic input patterns in neonatal- and adult-born GCs may be an intrinsic property determined already in their neuronal progenitors. If so, progenitors proliferating at different times in the animal’s life may generate GCs that do not revert their synaptic input patterns when challenged by heterochronic grafting.

We found that the synaptic input patterns are determined to a surprising extent already in progenitors. This determination progressively switched from neonatal to adult progenitors to generate characteristic synaptic input patterns of their neuronal offspring. These results provide evidence that neonatal and adult-born neurons originate from two progenitor populations that give rise to neurons with distinct synaptic input patterns.

RESULTS

Transition of synaptic development in postnatal life

During their synaptic maturation, adult-born GCs form higher densities of synapses in the proximal domain than in neonatal-born GCs. In the distal domain, neonatal- and adult-born GCs eventually reach similar synaptic densities. However, adult-born GCs form synapses in the distal domain later than neonatal-born GCs (Whitman...
and Greer, 2007; Kelsch et al., 2008; Bardy et al., 2010). We used these developmental differences to determine when GCs born between postnatal day (P)5 and adult age at P56 would change from a ‘neonatal’ to an ‘adult’ synaptic development in the two domains.

We labeled GC progenitors in the SVZ with replication-deficient oncoretroviruses. Oncoretroviruses have a short half-life and can only infect dividing progenitors (Sanes, 1989), thus enabling birth-dating of newly generated neurons. To visualize glutamatergic input synapses in the dendritic tree of single neurons, we expressed a genetic synaptic marker, PSDG, in GCs (Fig. 1). PSDG is a fusion protein between PSD-95 and GFP. PSD-95 is a protein localized to the postsynaptic density of glutamatergic input synapses (Sheng, 2001).

We infected GC progenitors in the SVZ with an oncoretrovirus encoding PSDG at P5, P20, P40 and P56 (Fig. 1). We examined GCs during the main period of synaptogenesis between 17 and 28 days post infection (dpi) when the differences in the distal and proximal domain are prominent between P5 and P56 generated GCs. The dendritic morphology of GCs was revealed by amplification of the low levels of diffusely distributed PSDG in the cytoplasm with antibodies raised against GFP, thus allowing measurements of synaptic densities in each of the dendritic domains. We observed that GC born at P20 had already switched to an ‘adult’ synaptic development in the proximal, but not in the distal domain (Fig. 1). In contrast to the proximal domain, the switch to an ‘adult’-like synaptic development occurred later in the distal domain. The complete adult pattern was observed only in GCs generated at P40.

**Grafting of GC progenitors**

Based on the above observations, we performed heterochronic grafting to determine whether the eventual differences in synaptic input patterns resides in the specialized properties of neonatal and adult progenitors or in the mature versus immature OB environment.

We first confirmed that our transplantation procedure did not produce carry-over of virus that could infect dividing progenitors in the host. In transgenic donor rats expressing β-Gal ubiquitously, we infected GC progenitors with a retrovirus encoding nuclear (NLS) mCherry (Fig. 2A–A″). Without transplantation, retrovirally labeled GCs in transgenic rats migrated from the SVZ to the GC layer of the OB, where 99.5% of mCherry’ cells also expressed β-Gal at 14 dpi (n=679 GCs). When labeled GC progenitors from the donor transgenic SVZ were transplanted to the SVZ of wild-type (non-
transgenic) hosts, 99.3% of mCherry+ GCs were also β-Gal+ in the GC layer of the OB at 14 dpi (n=542 GCs). These observations indicate that our procedure selectively labeled progenitors from the donor SVZ, and that there was no viral carry over that labeled progenitors in the host SVZ.

We also tested whether fusion of donor cells with host cells contributed to the labeling of cells in the host OB. We transplanted mCherry+ SVZ cells from wild-type rats to the SVZ of rats expressing β-Gal ubiquitously. In this experiment, cell fusion would give rise to GCs that express both the retroviral marker mCherry and the transgene β-Gal. Only one of 552 mCherry+ GCs in the transgenic hosts (at 14 dpi, n=12 host rats; Fig. 2B-B″), indicating that cell fusion was a rare event.
To determine the type of transplanted progenitor cell that was predominantly found in the host SVZ, we repeated the N→N grafting experiment under the same conditions, but instead of retroviral infection we used i.p. injection of BrdU (100 mg/kg body weight). BrdU, like oncoretroviruses, labels cells during cell division. Oncoretroviruses, however, need up to several days for robust expression of marker proteins (mCherry), whereas BrdU is immediately detectable. Twenty four hours after BrdU labeling, we transplanted SVZ cells and examined the host SVZ 6 h after grafting. In the host SVZ, out of the 416 BrdU+ cells, 98.9% expressed Mash1 (Ascl1), a marker for fast-amplifying progenitors, whereas only 16 out of 447 BrdU+ cells expressed doublecortin (DCX), a neuroblast marker (n=5 rats, Fig. 2C–C″). A control cohort of five littermate rats were injected with BrdU and examined without transplantation in parallel to the N→N group. Among these non-transplanted BrdU+ SVZ cells, 44.8% had Mash1 colocalization and 33.3% expressed DCX (n=419 and 679 cells, respectively, Fig. 2C–C″). These observations suggest that our transplantation procedure resulted in the selection of Mash1+ fast-amplifying progenitor cells.

Next, we examined the morphological differentiation of grafted GCs. GC progenitors were infected in the host with a retrovirus delivering a membrane-bound GFP that visualized their entire dendritic arbor. Iso- and heterochronically grafted or non-transplanted GCs derived from adult progenitors reached stages of their morphological maturation at the same dpi and eventually had dendritic trees of similar size (Fig. 2D–D″). In addition, GCs derived from neonatal and adult progenitors differed in the fraction of migrating cells at 14 dpi. This latter difference persisted after heterochronous grafting. After 14 dpi, however, no significant differences were detected between GCs derived from neonatal and adult progenitors. These observations suggest that early differences in the migration of GCs derived from neonatal and adult progenitors exist that are independent of the environment in which they differentiate.

To also test whether transplanted progenitors give rise to neurons with normal physiological properties, we performed targeted whole-cell recordings from N→N or non-transplanted neonatal-born GCs. Retroviral labeling with mCherry was performed as described in Fig. 3A. At 28-32 dpi, transplanted and non-transplanted GCs developed spontaneous synaptic glutamatergic inputs (sEPSCs) of similar frequencies and amplitude (n.s., Mann-Whitney test, n=15 GCs, respectively; Fig. 3A–B″), as well as comparable action-potential discharge upon current injection in N→N and non-transplanted GCs (n=15 GCs, respectively, n.s., ANOVA; Fig. 3C,D). In addition, the resting membrane potential (mean±s.e.m. : −68.5±1.6 mV and −70.4±2 mV), the membrane resistance (1.1±0.2 GΩ and 1.0±0.1 GΩ), and the membrane capacitance (7.0±0.5 pF and 7.6±0.5 pF) were similar in N→N and non-transplanted GCs, respectively (all n.s., t-test, n=15 cells), indicating that transplanted progenitors gave rise to GCs that integrated appropriately into the host circuit.
Grafting conditions

A grafting conditions

B distal domain

B' proximal & basal domain

C distal domain

C' proximal domain

C' proximal domain

C' basal domain

Fig. 4. Synaptic input patterns of GCs derived from neonatal progenitors. (A) Neonatal progenitors were simultaneously grafted either to the host neonatal (N→N) or adult SVZ (N→A). (B,B') Maximum density projection of the (B) distal, and (B') proximal and basal domain from PSDG+ N→N and N→A GCs at 28 dpi. Scale bars: 10†. (C-C') Cumulative plots of PSDG+ cluster densities for N→N and N→A GCs at 28 and 56 dpi in the (C) distal, (C') proximal, and (C') basal domain (n=23-25 GCs for each plotted data point). To test for consistency of the observed pattern of synaptic development upon transplantation, we repeated the N→A transplantations with a second blinded experimenter and replicated the same pattern (2). Right: statistical comparison (mean±s.e.m.) of the data shown on the left (ANOVA).

Grafting of neonatal GC progenitors

We then examined the pattern of PSDG+ input synapses of neonatal-born GCs upon grafting of their progenitors (Figs. 3E and 4). Only before 17 dpi, differences in the stage of dendritic outgrowth were detectable between GCs derived from neonatal and adult progenitors (Fig. 2D-D”). Hence, we focused on GCs at 28 and 56 dpi when they had reached their final synaptic densities. The N→N GCs acquired the same densities of PSDG+ clusters in their dendritic domains as non-transplanted neonatal-born GCs (supplementary material Fig. S2). Surprisingly, N→N and N→A GCs developed the same PSDG+ synapse densities in their dendritic domains (Fig. 4B-C”). Neonatal-born GCs have lower densities of synapses in the proximal domain than do adult-born GCs (Kelsch et al., 2008). Comparable with non-transplanted neonatal-born cells, N→A GCs maintained lower densities of the proximal synapses than in A→A GCs (at 28 and 56 dpi: P<0.001, t-test, respectively, for comparison of data from Figs 4C’ and 5C’), further supporting the observation that N→A GCs retained their neonatal synaptic input patterns. Furthermore, in the distal domain, the glutamatergic input synapse is colocalized and functionally coupled with an inhibitory output synapse. To analyze densities of these output synapses, we used SypG, a synaptophysin-GFP fusion protein. Synaptophysin is a protein that is localized to presynaptic neurotransmitter vesicles and SypG expressed with retroviral vectors can be used to label output synapses genetically (Meyer and Smith, 2006; Kelsch et al., 2008). In line with coupled input and output synapses in the distal domain, N→N and N→A GCs had similar densities of SypG+ clusters (supplementary material Fig. S2B). These observations reveal that the synaptic input patterns of neonatal-born GCs are an intrinsic property that is maintained independently of whether they differentiated in a mature or immature OB.

Grafting of adult GC progenitors

We then examined the pattern of PSDG+ input synapses of adult-born GCs upon grafting of their progenitors (Fig. 5). A→A GCs maintained the synaptic densities of non-transplanted adult-born GCs (supplementary material Fig. S3) with higher PSDG+ cluster densities in their proximal domain than N→N GCs (at 28 and 56 dpi: P<0.001, t-test, respectively, for comparison of data from Figs 4C’ and 5C’).

We analyzed the densities of PSDG+ synapses in the dendritic domains of A→N GCs at 28 and 56 dpi (Fig. 5B-C”). In the distal and proximal domains, A→N GCs failed to reach the densities of PSDG+ clusters characteristic of A→A GCs. In addition, when compared with N→N GCs, the densities of PSDG+ clusters of A→N GCs were significantly lower in the distal domain at 28 and 56 dpi (P<0.001, t-test, respectively, for comparison of data from Figs 4C and 5C). This latter observation indicates that adult-born GCs did also not adopt a ‘neonatal’ wiring pattern when they differentiated in the neonatal brain. Importantly, PSDG+ clusters in the basal domain of A→N and A→A GCs reached similar densities (Fig. 5C”), suggesting that A→N GCs can still form normal synaptic densities in at least one domain. In the distal domain, A→N and non-transplanted GCs had their PSDG+ clusters equally located in spines (supplementary material Fig. S4) and 97.4% of PSDG+ clusters were contacted by a presynaptic protein, bassoon, at 28 dpi (n=346 synapses, Fig. 6A), supporting the observation that PSDG in transport vesicles did not significantly contribute to the detected PSDG+ clusters of mature GCs and that genetically tagged PSDG+ clusters represented bona fide synapses. Consistent with reduced densities of glutamatergic input in the distal domain, the density of spine protrusions (Fig. 6B) and of SyG” output synapses (Fig. 6C) was also reduced in this domain of A→N compared with A→A GCs.

Properties of heterochronically grafted GCs

In the neonatal and adult SVZ, deep and superficial GCs are generated (Kelsch et al., 2007; Merkle et al., 2007), even though...
more deep cells are produced in adult animals (Lemasson et al., 2005). Both deep and superficial GCs switch from a ‘neonatal’ to an ‘adult’ synaptic input patterns while the animal grows up (Kelsch et al., 2008). In line with ‘adult’ synaptic input patterns in deep and superficial A→N GCs, both had the same reduced PSDG⁺ cluster densities upon transplantations (Fig. 6D).

To examine the function of glutamatergic inputs to A→N GCs, we performed targeted whole-cell recordings from A→A and A→N GCs at 28-32 dpi (Fig. 6E) that had been virally labeled as described in Fig. 3A. Electrical stimulation in the GC layer was used to activate synaptic EPSCs in the perisomatic region followed by stimulation in the external plexiform layer to activate inputs to the distal domain. All recordings were performed with gabazine (10 µM) to prevent co-activation of inhibitory inputs. In A→N GCs, the amplitude of perisomatic inputs had faster rise times than did distal stimulation (0.98±0.15 and 4.38±0.65, respectively, in six GCs, \(P=0.0005\), \(t\)-test). In addition, the decay times were faster for perisomatic inputs than for distal stimulation (4.35±1.02 and 17.6±2.59, respectively, in six GCs, \(P=0.0008\), \(t\)-test) and sEPSCs were blocked by the AMPAR antagonist CNQX (10 µM) at the end of the recording (Fig. 6E).

These results support the notion that, although their synaptic densities were reduced, A→N GCs still formed functional synapses. The rise times of proximal and distal EPSC inputs to 28- to 32-day-old A→A GCs were 1.07±0.17 and 4.13±0.52, respectively, in five GCs (\(P=0.0007\), \(t\)-test), suggesting that the dendritic excitability was similar in A→A and A→N GCs as revealed by the comparison of the rise times of their respective perisomatic and distal glutamatergic inputs (both n.s., \(t\)-test).

Finally, we tested whether spine or synapse densities already differed between A→A and A→N GCs by 21 dpi. As described by Whitman and Greer (2007), the increase in spine density (Fig. 6B) preceded that of the increase in synapses revealed by synaptic marker proteins (Fig. 7). There was no significant difference in spine density between A→A and A→N GCs at 21 dpi, suggesting that the initial spine formation is preserved (Fig. 6B). In addition, the densities of glutamatergic synapses in the distal and proximal domain were comparable in A→A and A→N GCs at 21 dpi (Fig. 7). In the proximal domain, A→N GCs initially formed high densities of PSDG⁺ synapses at 21 dpi (Fig. 7), that were lost during further maturation (28 dpi, Fig. 5), suggesting that synapse maturation rather than initial spine formation is impaired after A→N transplantation.

**DISCUSSION**

This study revealed the influence of intrinsic properties of Mash1⁺ progenitors on the formation of distinct synaptic input patterns, a feature central to synaptic wiring. In particular, GCs generated from neonatal progenitors maintained their ‘neonatal’ synaptic input patterns independently of whether they differentiated in a neonatal or adult circuit. However, GCs generated from adult progenitors differentiating in the neonate, developed neither a ‘neonatal’ nor an ‘adult’ synaptic input pattern. These findings support the finding that neonatal and adult progenitors generate GCs with distinct programs for the formation of synaptic input patterns.
Heterochronic grafting of progenitors

We chose grafting of retrovirally labeled progenitors to address the role of circuit environment and intrinsic programs in the generation of different wiring patterns. Using this procedure, oncoretroviral infection only labeled cells from the donor, but not in the host SVZ, and cell-fusion of donor cells with host SVZ cells did not contribute to GCs in the host OB upon grafting. The grafted progenitors expressed Mash1, which is indicative of fast-amplifying progenitor cells. For direct comparison of the different grafting conditions, progenitors were grafted iso- and heterochronically from the same donor animal. The neuronal offspring of isochronically grafted progenitors maintained the timing of their maturation steps and developed functional synaptic densities similar to non-transplanted GCs.

We chose genetic synaptic tags as they allow quantification of synaptic densities in each dendritic domain of a single neuron. The differences in domain-specific input densities distinguish ‘neonatal’ and ‘adult’ wiring patterns. Recordings of synaptic events would also allow quantification of synapse numbers, but not attribution of inputs to specific domains such as basal or proximal inputs. Local synaptic stimulation or glutamate uncaging along the dendrite can be used to determine the site of input at the respective domain, but will not easily allow quantification of synapse densities. A potential concern related to overexpression of PSD-95 is that it has been demonstrated to induce plasticity of glutamatergic synapses (El-Husseini et al., 2000; Nikonenko et al., 2008; Taft and Turrigiano, 2014). For example in the work of El-Husseini et al. (2000), overexpression was tenfold higher than the endogenous PSD-95 level, while retroviral expression only doubled the endogenous level.
The specification of SVZ progenitors may not only dictate the neurotransmitter phenotype and the position of the neurons in different layers (Hack et al., 2005; Merkle et al., 2007; Rakic et al., 2009), but may also be linked to the formation of characteristic synaptic input patterns. This is supported by the finding that GC derived from neonatal progenitors maintained their characteristic synaptic input patterns regardless of whether they matured in the adult or neonatal circuit. Other features also persisted in the synaptic development. As previously described (Whitman and Greer, 2007), adult-born GCs first showed an increase in spine densities followed by the maturation of synapses, as revealed by synaptic marker proteins. Interestingly, this dissociation persisted after heterochronous grafting. Furthermore, N→A GCs also retained their typical early increase in synapse density in the distal domain, whereas these synapses formed late in adult-born GCs (A→A or non-transplanted). The observation that GCs derived from neonatal and adult progenitors retained their respective ‘neonatal’ and ‘adult’ wiring patterns upon grafting to the adult host revealed that the circuit itself permits for variable wiring patterns. These GCs originated from transplanted Mash1- fast-amplifying cells. Thus, at least at this stage progenitors are relatively committed to give rise to a specific synaptic input pattern. It is, however, very possible that at earlier stages, such as the slowly dividing stem cells, these properties are not yet determined. We had observed that GCs derived from neonatal and adult progenitors already differ in their migration and outgrowth of their dendrites. This difference persisted when the progenitors differentiated in a heterochronous environment. It is therefore possible that some of these early differences will, through yet unknown mechanisms, still influence the eventual synaptic patterns of GCs. Yet these differences in migration and the stages of dendritic outgrowth were detected only before 17 dpi.

Another feature of synaptic wiring is cell type-specific connectivity. Progenitors are determined to generate deep or superficial GCs that connect to one of two types of projection neurons (Kelsch et al., 2007; Merkle et al., 2007). These two types of projection neurons form independent subcircuits in the OB. The switch from ‘neonatal’ to ‘adult’ synaptic input patterns occurs both in deep and superficial GCs, suggesting that cell type-specific connectivity and synaptic input patterns are determined independently. These progenitor programs may provide a framework based on which activity-dependent plasticity can generate further variations in the synaptic input patterns depending on the animals’ current environment.

**Intrinsic determination of synaptic input patterns**

The dendritic domains receive glutamatergic inputs from different neuron types and brain regions. The output of a neuron to the circuit depends on the number of synaptic inputs it forms with the different neuron types. In this study, we could infer from changes of synaptic densities that the numbers of synapses in a dendritic domain changed as the length of the dendrite remained stable upon iso- or heterochronous grafting.

Furthermore, N→A GCs maintained their lower ‘neonatal’ numbers of input synapses in the proximal domain compared with adult-born GCs. The proximal domain receives cortical inputs that globally excite GC and thereby boost dendrodendritic inhibition in the distal domain. Differences in the number of inputs to the proximal domain are therefore likely to impact GC inhibition during active olfactory processing and learning. In the distal domain, GCs usually form only one synaptic contact with each projection neuron dendrite (Woolf et al., 1991). Thus, A→N GCs, which had lower neuronal PSD-95 content (Kelsch et al., 2008). This retroviral expression of PSDG does not alter the amplitude or frequency of glutamatergic synaptic inputs (Kelsch et al., 2008). In further support, two other readouts (i.e. the synaptic marker SypG and spine densities visualized by membrane-tagged GFP) revealed similar changes in PSDG+ synapse densities.

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**Interaction of intrinsic determination and circuit environment**

Grafting of adult progenitors also revealed a crucial role for the host circuit during the formation of synaptic input patterns. GCs originating from the same adult progenitors readily completed their characteristic synaptic input patterns in their isochronous (adult), but not in a heterochronous (neonatal) OB. Importantly, GCs derived from adult progenitors neither maintained their characteristic ‘adult’ synaptic densities, nor did they adopt the fate typical of neurons in the ‘neonatal’ host OB. Compatible with this finding, it has been shown that certain molecules are upregulated in the adult OB, such as tenasin-R, which influences the maturation of adult- not neonatal-born GCs (David et al., 2013).

Interestingly, heterochronous grafting of adult progenitors resulted in GCs with reduced synapse densities both in the distal and
proximal domain. We now observed that GCs generated at different times in postnatal life switched from ‘neonatal’ to ‘adult’ formation of synaptic input patterns independently in the proximal and distal domain. The switches from ‘neonatal’ to ‘adult’ patterns did not revert, as revealed by heterochronic grafting of adult progenitors. These observations provide further evidence that adult neurogenesis is not a simple continuum of neurogenesis during brain development. As neonatal- and adult-born GCs also differ in other properties of their synaptic organization (Kelsch et al., 2009; Nissant et al., 2009; Bardy et al., 2010; Valley et al., 2013), future studies may address whether these differences also arise from switches in the progenitor fate.

The intrinsic properties of progenitor cells controlling synaptic wiring may need to be considered for repair strategies. In particular, neural stem cells appear to be specified to generate interneurons that cannot be easily converted towards generating of other neuronal subtypes (Weinandy et al., 2011). It will be crucial to determine whether synaptic input patterns are determined only at the fast-amplifying progenitor stage or already at the level of slowly dividing stem cells. Taking into consideration the limited adaptability of intrinsic properties of neuronal progenitors, the repair of brain circuits by neuronal replacement strategies may require engineering of neuronal precursors to produce new neurons that match the properties of the target circuit.

MATERIALS AND METHODS

Animals and husbandry

Adult female (>P56) and neonatal (P5) Sprague-Dawley rats were obtained from Charles River and housed in groups of three or four adult female rats under standard conditions at a 12 h day/night cycle. Pups were weaned at P28. All procedures were approved by the local animal welfare committee (RP Karlsruhe, permission number 35-9185.81/G-186/10) and in accordance with NIH guidelines. Transgenic reporter ratsCAG-loxP.LacZ.STOP.loxP-EGFP with ubiquitous expression of nuclear localized (NLS) β-Gal (Schönig et al., 2012) were bred in a Sprague-Dawley background.

Retroviruses

Oncoretroviral vectors derived from Moloney Leukemia virus with an internal promoter derived from the LTR from the Ross Sarcoma Virus (RSV) were generated by replacing the membrane-bound (palmitoylated) GFAP with the open reading frame of PSDG or SyrG to visualize glutamatergic post-synaptic clusters or presynaptic release sites, respectively, or NLSmCherry. Recombinant virus was prepared and stored as described previously (Lois et al., 2002). The viral titer was 10^6-10^7 infectious units/µl.

Stereotactic surgery and transplantation procedure

Adult animals were anesthetized with isoflurane and neonatal animals by ketamine/xylazine compared with isoflurane anesthesia. Adult animals were anesthetized with isoflurane and neonatal animals by ketamine/xylazine compared with isoflurane anesthesia. Stereotactic surgery and transplantation procedure

Histology

The animals were euthanized with an overdose of isoflurane followed by transcardiac perfusion with PBS at 35°C for 30 s and subsequently paraformaldehyde (4% in PBS, Roth) at room temperature for 3 min. Brains were removed and post-fixed in paraformaldehyde overnight. Coronal sections (50 µm) were prepared with a vibratome. For visualization of genetic synaptic markers, tissue sections were incubated in rabbit anti-GFP primary antibody (1:10,000, Millipore) diluted in blocking solution containing PBS, 0.3% Triton X100 and 1% bovine serum albumin at 4°C overnight. Sections were washed three times in PBS and then incubated with Cy-3 conjugated anti-rabbit secondary antibody (1:1500, Jackson ImmunoResearch) in blocking solution at room temperature for 2 h. Sections were again washed three times in PBS and mounted on slides with Gelmount (Sigma). For labeling of presynaptic sites, mouse anti-Bassoon (1:1000, VAM-PS003, Enzo Life Science) and rabbit anti-GFP primary (1:10,000) and A555-conjugated anti-mouse (1:1000, Molecular Probes) and Cy5-conjugated anti-rabbit (1:1500, Jackson ImmunoResearch) secondary antibodies were used. For control experiments using β-Gal reporter rats, anti-rabbit β-Gal primary (1:4000, MP Biomedicals) and A488-conjugated anti-rabbit secondary antibodies (1:1000, Molecular Probes) were used. For BrDU immunohistochemistry, tissue sections were pre-treated with 2 M HCl for 1 h at room temperature. Primary antibodies were rat anti-BrDU (1:400, Santa Cruz) and goat anti-DCX (1:500, Santa Cruz) and mouse anti-Mash1 (1:500, BD Biosciences). Colocalization was determined from confocal sections (63× oil objective) of the same SVZs double-immunostained for BrDU and Mash1 or BrDU and DCX.

Blinding of the experiment

After perfusion of the animal, the conditions were blinded by labeling the respective brains with a random combination of letters and handed over to the second experimenter. All data were acquired by providing the second experimenter with only details of how many GCs had to be acquired from each batch of brains to eventually obtain 25 measurements per condition, dpi and domain. This second experimenter was instructed to take only five images per brain for each domain to avoid uneven sampling from single animals. Synaptic densities were quantified for all conditions. Once analysis was completed, we confirmed that all time-points contained 25 neurons per condition (or at least 23 neurons). If it was fewer than 23 neurons, additional neurons were imaged. If it was more than 25 neurons, only the first 25 imaged neurons were included. Once this step was completed, data were unblinded and statistically analyzed.

Morphological analysis

Vibratome sections (150 µm) were incubated with rabbit polyclonal anti-GFP antibody (1:5000) at 4°C for 24 h. Sections were sequentially incubated with biotinylated secondary antibody and with peroxidase-avidin-biotin complex (both biotinylated goat anti-rabbit and ABCComplex from Vector Laboratories) and visualized with 3,3′-diaminobenzidine (DAB). Morphological reconstruction of the neurons and their processes was performed using the Neurolucida system (MBF Bioscience) with a...
100× oil-immersion objective (Zeiss Imager). Morphological differentiation was staged based on previously described criteria (Petréanu and Alvarez-Buylla, 2002). The densities of spine-like protrusions were quantified along the distal dendritic tree using a Neurulocida System (100× oil objective). Each protrusion emerging from the dendritic shaft of GFP-labeled GCs was counted as a single protrusion. Neurons were visualized by anti-GFP immunohistochemistry followed by DAB reaction.

**Image analysis**

Confocal image stacks were acquired using a Leica SPM5 laser scanning microscope (63× oil-immersion lens, 1.4 numerical aperture) (pixel size 0.23×0.23 μm, 512×512 pixel) with a z-step of 0.25 μm (80–150 sections). Image acquisition settings of the confocal microscope were initially determined with 28 dpi non-transplanted GCs expressing PSDG and kept constant throughout the study. Maximal intensity projections were used to measure the density of PSDG+ or SynG+ clusters of a dendritic segment with morphometry analysis of ImageJ software. The proximal domain was defined as the first 25 μm of the apical dendrite emerging from the soma. Contact of PSDG+ clusters with the presynaptic marker protein Bassoon was determined in confocal stacks that were imaged as described above. The fluorescent clusters did not overlap in their center, but in their borders. Bassoon+ clusters were located outside the PSDG+ cluster-containing spine. The spines and dendrites of GCs were visualized by immunofluorescence against GFP with a Cy5-tagged secondary antibody. The same results were obtained in these animals by immunofluorescence against the presynaptic marker VGlut1 (anti-guinea-pig antibody, 1:1000, Millipore) where 208 out 210 PSDG+ clusters were contacted by VGlut1+ puncta (supplementary material Fig. S4A).

**Electrophysiology**

Animals were given an overdose of isoflurane and perfused transcardially with carbomediated slicing solution at 4°C containing (in mM) 212 sucrose, 3 KCl, 1.25 NaH2PO4, 26 NaHCO3, 7 MgCl2, 0.5 CaCl2 and 10 glucose (306 mOsm, pH 7.3). Bulbs were incubated in ice-cold slicing solution and cut into 350 μm sagittal slices with a vibratome. For recovery, slices were incubated at 32°C for 30 min in carbogenated recording solution containing (in mM) 125 NaCl, 2.5 KCl, 1.25 NaH2PO4, 25 NaHCO3, 1 MgCl2, 2 CaCl2 and 25 glucose (312 mOsm, pH 7.3). Fluorescence-guided whole-cell patch clamp recordings were performed with an EPC-10 amplifer (HEKA). The pipette solution contained the following (in mM): 4 KCl, 140 K-gluconate, 10 HEPEs, 0.4 ATP-Mg, 0.3 GTP-Tris and 10 phosphocreatine (292 mMol, pH 7.2). Lucifer yellow (Sigma) was added to pipette solution (1 mg/ml). Access resistance was <20 MΩ.

**Competing interests**

The authors declare no competing financial interests.

**Author contributions**

N.R., L.-L.O. and W.K. performed the experiments and analyzed data. K.S. and D.B. contributed reagents, N.R. and W.K. wrote the manuscript.

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**Supplementary material**

Supplementary material available online at http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.110767/-DC1

**References**


