



# Royal Netherlands Academy of Arts and Sciences (KNAW) KONINKLIJKE NEDERLANDSE AKADEMIE VAN WETENSCHAPPEN

## Adult neurogenesis, human after all (again)

Lucassen, Paul J; Fitzsimons, Carlos P; Salta, Evgenia; Maletic-Savatic, Mirjana

### **published in**

Behavioural Brain Research  
2020

### **DOI (link to publisher)**

[10.1016/j.bbr.2019.112458](https://doi.org/10.1016/j.bbr.2019.112458)

### **document version**

Publisher's PDF, also known as Version of record

### **document license**

CC BY-NC-ND

[Link to publication in KNAW Research Portal](#)

### **citation for published version (APA)**

Lucassen, P. J., Fitzsimons, C. P., Salta, E., & Maletic-Savatic, M. (2020). Adult neurogenesis, human after all (again): Classic, optimized, and future approaches. *Behavioural Brain Research*, 381, 112458. <https://doi.org/10.1016/j.bbr.2019.112458>

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

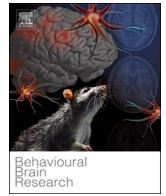
- Users may download and print one copy of any publication from the KNAW public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the KNAW public portal.

### **Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

### **E-mail address:**

[pure@knaw.nl](mailto:pure@knaw.nl)



## Adult neurogenesis, human after all (again): Classic, optimized, and future approaches

Paul J. Lucassen<sup>a,\*</sup>, Carlos P. Fitzsimons<sup>a</sup>, Evgenia Salta<sup>b,c</sup>, Mirjana Maletic-Savatic<sup>d</sup>

<sup>a</sup> Swammerdam Institute for Life Science, Center for Neuroscience, University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, The Netherlands

<sup>b</sup> Netherlands Institute for Neuroscience, Meibergdreef 47, 1105 BA, Amsterdam, The Netherlands

<sup>c</sup> VIB Center for Brain and Disease Research / KU Leuven, Department of Neurosciences, Leuven Brain Institute, Herestraat 49, 3000, Leuven, Belgium

<sup>d</sup> Baylor College of Medicine and Jan and Dan Duncan Neurological Research Institute at Texas Children's Hospital, Houston, TX, USA

### ABSTRACT

In this perspective article, we reflect on the recent debate about the existence of human neurogenesis and discuss direct, and also indirect, support for the ongoing formation, and functional relevance, of new neurons in the adult and aged human hippocampus.

To explain the discrepancies between several prominently published human studies, we discuss critical methodological aspects and highlight the importance of optimal tissue preservation and processing for histological examination.

We further discuss novel approaches, like single-cell/nucleus sequencing and magnetic resonance spectroscopy, that will help advance the study of human neurogenesis to its fullest potential – understanding its contribution to human hippocampal functions and related disorders like depression and dementia.

### 1. Introduction

For most of us, the question of whether adult neurogenesis exists in the human brain was a no-brainer. After all, over the past two decades, its presence had been reported by several landmark studies that applied independent approaches and had demonstrated the generation of new neurons in the postnatal/adult human brain ('adult' from now on, for brevity) in at least two regions, *i.e.* the subgranular zone (SGZ) of the hippocampus and the subventricular zone (SVZ) [1–5]. Using immunocytochemistry, neurogenic markers have also been observed in other species and other brain regions, such as the entorhinal and neocortex, olfactory bulb, amygdala, striatum, spinal cord [6–17,247]. Also in the hypothalamus of mouse, sheep and human brains, neurogenic changes occur [18–23], while the C14 approach (see below) has further identified neurogenesis also in the human striatum. For many of these regions, this awaits further confirmation in human brain, and we therefore focus this perspective on human hippocampal neurogenesis only.

Historically, the first evidence of human adult neurogenesis was based on bromodeoxyuridine (BrdU) pulse-chase experiments, traditionally used to label dividing cells in live tissue and to trace their (surviving) progeny using subsequent immunofluorescent labeling of fixed tissue. Using this BrdU approach, neurogenesis was demonstrated in a small series of postmortem hippocampal samples of cancer patients where BrdU had been injected for diagnostic purposes [1].

Another way to detect adult neurogenesis was carbon 14 (<sup>14</sup>C)

birth-dating. This approach takes advantage of the nuclear-bomb-tests-derived rise in atmospheric <sup>14</sup>C and its incorporation into genomic DNA, which allows to measure cellular age and demonstrate cell renewal of pre-sorted neuronal NeuN + nuclei. Although ingenious, <sup>14</sup>C-dating uses complex methodology and requires unique equipment [24,5]. Perhaps for these reasons, the <sup>14</sup>C approach has so far not been replicated by other groups.

In yet another approach, neurogenesis is studied in *in vitro* cell-based models [25] and stem cells and/or neuroblasts are isolated from human postmortem hippocampi to demonstrate their capacity to form neurons *in vitro* [2,4,26]. More conventional immunocytochemical methods furthermore, using markers such as Ki-67, proliferating-cell-nuclear antigen (PCNA) and doublecortin (DCX), have also identified ongoing proliferation and young, migratory neurons in human post-mortem samples (for references see below).

To the scientific community focused on adult hippocampal neurogenesis, it was therefore at least surprising that all this evidence was apparently overlooked when a single paper reporting a negative finding, *i.e.* a failure to detect neurogenesis in the adult human hippocampus, was published in *Nature* in 2018 [27]. In this paper, a unique age series of hippocampal control samples was investigated, together with monkey samples and neurosurgical specimens from epilepsy patients. The authors reported that the number of proliferating progenitors and young neurons in the dentate gyrus declined sharply during the first years of life to negligible amounts by 7 and 13 years of age. Also, in epilepsy patients and in adult monkeys, young hippocampal neurons

\* Corresponding author.

E-mail address: [p.j.lucassen@uva.nl](mailto:p.j.lucassen@uva.nl) (P.J. Lucassen).

<https://doi.org/10.1016/j.bbr.2019.112458>

Received 31 May 2019; Received in revised form 29 November 2019; Accepted 28 December 2019

Available online 30 December 2019

0166-4328/ © 2020 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

were not detected. This led the authors to conclude that “neurogenesis in the dentate gyrus does not continue, or is extremely rare, in adult humans” and raise questions about its functional relevance in humans.

Due to its high public exposure, [27] and related papers [28,29] triggered considerable debate and often significant doubt, both in a part of the scientific community (see [30] for example) and in popular laymen media, regarding the existence of neurogenesis in adult humans. Shortly after Sorrells et al. was published however, another study, using very similar immunocytochemical methods, reported the exact opposite, *i.e.* an abundant presence of neural precursor markers throughout the human lifespan [31]. Similar findings have since then been published by two other, independent groups [32,33], altogether calling for a reflection on what might explain these discrepancies, what can be learned for future studies, and what still remains unknown.

After a brief historical overview, we here reflect on this dynamic period and discuss direct and indirect support for the existence of human neurogenesis and its possible involvement in disease. We close by highlighting future approaches and listing outstanding questions that will help advance the field of human neurogenesis and improve our understanding of its role in health and disease.

## 2. A short overview of the evidence for adult human neurogenesis

Throughout its development, the field of adult neurogenesis has been very lively and seen many challenges and controversies [34]. Major steps forward were often driven by the introduction of new technologies in combination with access to unique tissue samples. The first descriptions of new cell birth were observed in the 1960s and 1980s and based on tritiated ( $^3\text{H}$ ) thymidine incorporation into dividing DNA in the brains of adult rodents and birds ([35,36]; see also [37] and [38] for reviews). Due to concerns about the then new methodology to label the dividing cells with  $^3\text{H}$ -thymidine, the initial reports were received with skepticism and the topic did not receive much follow-up for nearly 2 decades [39]. Moreover, the attempts to detect newborn cells in the hippocampus of non-human primates after puberty were not fruitful [40–42], and hence it was generally assumed that adult neurogenesis was likely also irrelevant for humans.

Another reason for the slow progress was due to methodological limitations: the pulse-chase labeling with  $^3\text{H}$ -thymidine was cumbersome and hard to work with, and more importantly, conclusions about the phenotype of the newborn cells could not easily be drawn. When non-radioactive thymidine analogues such as BrdU, CldU, and IdU became available, together with the development of confocal microscopy and of antibodies directed against these analogues, and against specific cell cycle and cell type markers, this new experimental ‘toolkit’ opened up possibilities for many laboratories to detect neurogenesis in rodents. [1] were the first to use such an approach on a unique set of hippocampi obtained from five cancer patients and could identify new cell formation and neuronal differentiation, confirming the overall location and extent of neurogenesis as seen in rodents (reviewed in Ernst and Frisen, 2015).

This landmark paper was followed by more conventional immunocytochemical studies on postmortem samples, confirming the presence of dividing, proliferating and/or neuronal precursor cells (NPCs) in the human hippocampus [43–55,245–246]. Studying the actual phase of adult neurogenesis, however, proved to be more challenging in postmortem human brain tissues. For example, the morphology and numbers of DCX-expressing cells reported in various papers on human brain [43,29,56–59] differ considerably from those reported in rodent brain (see for example [60–62]) and even astrocyte-like morphologies of DCX-positive cells were observed in human cortex [63]. In particular the dendritic extent of DCX-positive cells in the hippocampus appeared sensitive to postmortem delay induced breakdown, as was observed in a postmortem series of rat hippocampi ([43], Dr Schmitt-Bohrer, University of Wurzburg, personal communication). As the morphology of DCX-positive cells in human brain, for obvious

reasons almost always immersion-fixed in formalin after a given postmortem interval, also lacks the extensive dendritic staining pattern that is so prominent in rodent brains that are generally perfusion-fixed with 4% paraformaldehyde in PBS, this indicates fixation may be critical in explaining differences between findings in rodents or humans. In their extensive methodological optimization studies, [32] now demonstrated that (prolonged) fixation in formalin indeed reduced DCX-immunoreactivity. Since this is generally prolonged for most human brains, also fixation time is a critical variable to consider when detecting these neurogenic markers.

A third line of evidence in support of human neurogenesis made use of the nuclear bomb tests that occurred during the cold war period around the 1950s and 60s. Few labs can perform these types of analyses, but the  $^{14}\text{C}$  technique to birthdate DNA has demonstrated the presence of adult-generated cells in the human hippocampus [5] and also the birth of new oligodendrocytes in the cortex [64]. Due to its radioactive nature, C14 can be detected in a more reliable and quantitative manner than other techniques used to estimate neurogenesis, such as immunocytochemistry. The C14 approach can detect a low but stable level of human hippocampal neurogenesis, that remained present throughout life, comparable to levels observed in a middle-aged mouse ([5]; Ernst and Frisen, 2015). In contrast to rodents, neurogenesis could not be detected in the human olfactory bulb with this approach [65]. Surprisingly, and unlike the rodent brain, large numbers of newborn cells were found in the human striatum using the C14 approach, pointing to distinct species-specific differences [9,24,14].

In contrast to the evidence above, the papers by [27,29] and [28] have been interpreted as evidence for an absence of neurogenesis in the adult human brain. However, these particular papers report the *absence of evidence*, *i.e.* a failure to detect neurogenesis. Although the putative positive and negative controls included in their studies may support this interpretation as a possible conclusion, this can, in light of findings by others that were positive, and the limitations stemming from their samples and methodologies, not be considered as conclusive *evidence of absence*, as discussed below.

## 3. Is there adult neurogenesis in the human hippocampus or not?

Following 2 related papers [28,29], [27] examined various immunofluorescent markers in a unique series of hippocampal samples from 37 cases, that were considered controls and had died at different ages (ranging from 14 weeks of gestation to 77 years old), in an age series of monkey samples, and in 22 neurosurgical specimens from medically-resistant intractable epilepsy patients. The study had clear assets: i) rare embryonic and adult cases were studied in parallel; ii) rare surgical samples were obtained from epilepsy patients, serving as controls for the postmortem interval (*i.e.* absence of it); iii) multiple immunocytochemical markers, like Ki-67 and MCM2 as mitotic markers, SOX2 and BLBP as markers for radial glia-like stem cells (Type-1 cells) and DCX or PSA-NCAM as markers for early immature neurons (a.k.a. ‘neuroblasts’) and iv) electron microscopy were employed to identify specific stages of neurogenesis, and results were demonstrated in impeccable confocal images from infant brains, a.o..

The authors observed evidence of ongoing neurogenesis, largely based on DCX and PSA-NCAM immunocytochemistry, at early ages and reported that the number of proliferating progenitors and young neurons in the dentate gyrus declined sharply during the first years of life, and only few young neurons were observed by 7 and 13 years of age. In adult patients with epilepsy and in healthy human and monkey adults, young hippocampal neurons were not detected. Based on this standard immunocytochemical approach on conventionally fixed material, the authors concluded that “neurogenesis in the dentate gyrus does not continue, or is extremely rare, in adult humans”. Based on this, and given the continued presence of adult neurogenesis in other species, the authors raised questions about the functional relevance of neurogenesis in adult humans [27].

Amidst the debate that emerged following [27], only weeks later [31], published a study using very similar methodology, but instead reported a presence of human neuronal precursors throughout life, while acknowledging the decline in markers of stem cells and angiogenesis. Although the two studies used very similar approaches on comparable tissues, nearly opposite conclusions were reached, triggering considerable discussion in several follow-up papers [66–70].

This discussion appears to be settled now by the publication of [32], who addressed specifically many of the methodological concerns that were raised before in response to [27], regarding for instance the influence of fixation time and postmortem delay, among others [66,68]. They confirmed in a cohort of 58 subjects (13 neurologically healthy subjects and 45 patients with Alzheimer's disease) an extensive presence of DCX-positive, immature neurons, presumably at distinct maturation stages, from young ages onward up into the 10<sup>th</sup> decade. Similar findings of ongoing neurogenesis were reported by [33] in old individuals.

Although the rates of decline differed between studies, methods and antibodies used and the decrease was not always gradual, several earlier papers had generally shown a decrease in proliferation and neurogenic markers with increasing age [5,28,29,31,53,57]. The three recent studies now indicate that considerable numbers of neurogenic and DCX-positive cells remain present throughout life and can still be detected even in oldest old, healthy subjects and even suggest a link to cognition [32]; showed consistent and early reductions in neurogenesis in Alzheimer's disease (AD) patients, while [33] reported reductions in the numbers of DCX-positive (DCX+) cells double-labeled for PCNA in patients with mild cognitive impairment (MCI), a stage generally preceding dementia, with higher number of neuroblasts being associated with a better ante-mortem cognitive status [33].

#### 4. Possible explanations for the discrepancy between histological studies

Studying changes in neurogenesis with age or in disease cases can in general only be meaningful when they are compared to a carefully matched cohort of *true control*, *i.e. healthy, subjects*. Ideally, a thorough clinical documentation is available for each subject, including ethical approval, permission to use brain tissue for research purposes, and a systematic neuropathological investigation to confirm control or disease status [71]. Very little patient information was available in the cohort of [27], and based on what is available, many individuals may have died from a serious illness. Each of those - severe inflammatory disease, medications known to inhibit neurogenesis, chronic systemic toxic conditions - could have inhibited neurogenesis. Besides the direct biological effects of the underlying illnesses, many of the patients studied in Sorrells et al. must have suffered the conditions for a long time. This causes an additional caveat to the findings: disease or the prolonged, chronic stress that is often associated with it, or may precede the death process, is well established to reduce neurogenesis in preclinical models [72,62,73–75]. In contrast, both [31] and [32] took rigorous measures to ensure that their control subjects were indeed physically and psychologically healthy, and provided ample information on their subjects.

A second critical variable in human brain studies is the *postmortem interval*. Protein breakdown that occurs with increasing postmortem interval can affect immunocytochemical results [76] and good quality tissue is therefore critical with, ideally, postmortem intervals and fixation times that are kept as short as possible, and at least matched between groups. Sorrells et al. [27] gave no specific information on the time that lapsed between death and sample collection for their individual subjects, and stated that the postmortem interval was minimal 48 h, whereas the intervals in [32] and [33] were considerably shorter. A precise postmortem interval for each individual sample matters, however, because target antigens may decay at different rates following death and many of the neurogenesis markers studied could therefore have been affected by protein breakdown [76,43,32].

Next to postmortem interval, *agonal state* must be taken into account. Agonal state refers to the type and duration of the death process and is another important readout to match brain tissues for, as it is different between subjects. When the agonal state is prolonged, such as after a chronic disease and long death process, the brain pH becomes more acidic, whereas in subjects who die acutely, for instance because of a heart attack or traffic accident, brain pH remains more physiological [77,78]. Brain pH is known to affect post-translational modifications of proteins and RNA, and matching for agonal state is thus ideally included when comparing patients and controls. This is particularly relevant for patients who, for instance, died of broncho-pneumonia, that results in hypoxia and in a pronounced lactic acidosis of the brain, which can affect PSA-NCAM immunocytochemistry (see also [68]).

Moreover, also *fixation* of the brain tissue brings forward well-known effects. Prolonged fixation in formalin can mask specific antigens and prevent their detection with antibodies, as [32] have now clearly demonstrated for DCX. When fixation was short and tissue well preserved by avoiding freezing and paraffin embedding, and by avoiding any type of mechanical alteration, as was the case in their unique cohort, then many clear DCX-positive cells could still be observed up until old age, although some of these cells lacked the extensive dendritic staining pattern typical of the rodent hippocampus. In their extensive series of tests and parametrical validation in the methods section of their paper, they report that postmortem intervals up to 38 h did not affect the detection of DCX or PSA-NCAM in the number of cells, nor in the quality of DCX immunostaining, and thousands of DCX-expressing neurons could be identified in brains that were optimally preserved.

Prolonged fixation and masking effects of antigens are especially relevant when brain samples are fixed conventionally, as done in most medical/neuropathological centers, *i.e.* generally for one month or more in formalin followed by embedding in paraffin. This might imply that the standard fixation conditions in most brain bank collections could be suboptimal for neurogenesis studies. However, some of the deleterious masking effects of prolonged fixation on antigenicity can be rescued by antigen retrieval protocols, using for instance microwave or pressure-cooking with buffers at different pH values, or by aldehyde and autofluorescence elimination procedures. [31] and [33] have for instance shown that neurogenic signal can still be detected even in standard fixed tissues of the oldest old.

Taken together, different aspects of tissue processing, tissue block size, postmortem delay, fixation duration, agonal state, *etc.* that differ considerably between patients and laboratories, can all contribute to the variation observed in DCX signal and morphology in earlier human brain studies. In future studies, it will therefore be very important to extensively test and optimize pre-treatment protocols especially for conventionally formalin-fixed, paraffin-embedded tissues of post-mortem human brain; such efforts pay off as they can allow access to tissue collections in human brain biobanks worldwide and thereby enable researchers to compare larger groups of patients to matched control subjects.

Regarding the use and selection of *methodological controls*, [27] used resected human hippocampal tissues, which are indeed unique given the absence of a postmortem interval. Yet, since they were taken from epilepsy patients, such rare samples bring about additional sets of challenges. Only in extreme conditions of chronic and severe epilepsy, patients undergo such an invasive operation to remove the affected tissue, *i.e.* hippocampus. In rodent models, epilepsy strongly reorganizes the hippocampal network, promotes astrogliosis and/or depletes proliferating precursors [79]. Indeed, in a recent paper on surgically removed hippocampal human tissues of epilepsy patients, low levels of proliferating but also considerable numbers of immature neurons were observed [251], parallel to structural hippocampal abnormalities. The differences with [27] and related studies may be explained by different (timing and duration of) disease conditions and

tissue processing. Either way, it is very unlikely that after a prolonged disease duration, neurogenesis, as detected in resected epileptic tissue, still reflects the typical situation in control human brain.

Aside from the many different drug treatments these patients received, which may all affect neurogenesis, epilepsy and the operation itself are also expected to induce plasticity-related changes in the hippocampus, as reported ([80]; see also references in [68]). It is also possible for inflammation, extensively reported in epilepsy in both human and rodent models [81], to have altered neurogenesis *per se* [82], the antigen expression and/or their post-translational modification [83] in these medically-ill patients. Finally, as mentioned above, even patients with medically-resistant epilepsy requiring surgery may have different amounts of hippocampal neural stem cells (NSCs) [2]. It is thus difficult to rely on such tissue as “controls” for postmortem interval. Ideally, a proper control would be tissue resected from healthy subjects, which, for obvious reasons, cannot be obtained.

A main asset of [31–33] is further their use of *stereology*, considered essential for an unbiased quantification in histological analyses. Especially for relatively ‘rare’ events, measuring them in only a few thin tissue sections, taken at only a few anatomical levels, will likely miss many cells. The standard for publication of immunocytochemical data from the mouse hippocampus, much smaller than the human hippocampus, requires at least six series of equally spaced 30–50  $\mu\text{m}$  sections systematically sampled over the whole dentate gyrus [84]. Although stereological results are influenced by specific settings, such as the number of counting frames, regions of interests and sampling frequencies [85,86], it is considered important to take into account the entire anatomical structure when quantifying neurogenesis in the hippocampus, given the clear differences in (regulation and function of) neurogenesis between rostral and caudal parts [87–90].

Even though different tissue treatment and antibody protocols were used [31–33], they all used stereology and, in contrast to [16], came to the same conclusion, confirming ongoing neurogenesis up into the 8<sup>th</sup> and 9<sup>th</sup> decade of life. Hence, taken all the above together, the main lesson we learned from the human postmortem studies is that methodology and standardization matters, maybe even more so than for rodent work, as they are especially critical in detecting neurogenesis in postmortem human brain tissue.

## 5. Indirect evidence also supports human adult hippocampal neurogenesis

In addition to direct (histological) observations in human brain, there is also considerable indirect evidence supporting (a functional role for) human neurogenesis. This comes on the one hand from a variety of studies that have demonstrated hippocampal changes associated with neurogenesis in relation to functional changes in animal models. For instance, newly-generated neurons in the murine dentate gyrus contribute to spatial and fear learning and memory (processing) and to pattern separation [91–100], mood and anxiety and affect regulation [101], forgetting [102] and cognitive flexibility [103]. Neurogenesis and these processes can further be affected by environment, mood, drugs and stress [104–106,72,87,107–110], and modulate pattern separation, forgetting and/or spatiotemporal-emotional regulation [91,92,97,111,112].

Certain behavioral tasks, such as *pattern separation*, can be assessed in both mice and men, thus serving as indirect evidence or proxy also for functional human neurogenesis. Pattern separation depends on hippocampal adult neurogenesis and refers to the ability to discriminate and store similar, but not identical, inputs of sensory information into distinct representations [97]. Specific tasks, such as those developed by Kirwan and Stark [248] allow for specific measurements of pattern separation in humans. The so-called Stark test is a mnemonic similarity task that involves discriminating the visual similarities of two different, but similar, images. An increased performance on pattern separation while completing this task was associated with increased blood oxygen

level-dependent (BOLD) fMRI signal, selectively in the dentate gyrus [113–116], indirectly linking it to neurogenesis.

Decreased performance on pattern separation is furthermore a well-described phenomenon associated with hippocampal damage and cognitive impairment, both known to decrease neurogenesis and/or dentate gyrus size [115–119]. Moreover, Déry et al. found that anaerobic exercise was prospectively associated with improved performance on the mnemonic similarity task (Stark test) [120]. Interestingly, deficits in pattern separation are a common and early feature in dementia, whereas patients with depression did not perform well on Stark test compared to healthy matched controls. With anaerobic exercise, they not only improved their performance, but their depressive symptoms also declined [120].

To provide additional evidence that adult human hippocampal (NSCs) are present and functional, other groups isolated them from human hippocampal samples to study their potential for proliferation and *neuronal differentiation in vitro* [2,4,25,26]. [2], for example, assessed the neurogenic potential of human NSCs from the dentate gyrus obtained after surgical resections. Interestingly, the isolated adult human NSCs showed either a high or very low proliferative capacity *in vitro*, and surprisingly, patients who had stem cells with high proliferation capacity, had preserved memory performance prior to epilepsy surgery, while patients who had stem cells with a low proliferative capacity, suffered from severe learning and memory impairments.

Changes in neurogenesis may also be indirectly related to changes in *hippocampal volume* that often occur in close correlation with altered stress regulation. For example, prolonged stress-related conditions, such as depression, Cushing’s disease, or post-traumatic stress disorder (PTSD), are associated with reductions in hippocampal volume. This reduction could notably be reversed upon successful treatment in some conditions [121,122], indicating that a dynamic substrate such as neurogenesis might be involved [51,105,44,56,123,45,87], at least under stress-related conditions [109,123]. Moreover, prolonged physical exercise in humans, known to boost neurogenesis in rodents [104,124], increased the volume and functional connectivity of the hippocampus specifically, but did not affect other brain regions such as the striatum [125,126].

While earlier studies examined hippocampal volume as a whole, [127] subfractionated it and recently reported on specific subregional changes in depressed patients who were treated with electroconvulsive therapy (ECT), an effective treatment for patients with medically-resistant depression. In rodents, ECS (electroconvulsive shock) strongly increases the extent of neurogenesis [128,129] while high levels of proliferation had been observed in a postmortem study in one patient who had received ECT [51]. [127] used 7 T magnetic resonance imaging with detailed subfield segmentation to detect specific volume changes in subfields of the hippocampus and found a selective, and substantial increase in volume, specifically of the dentate gyrus after ECT treatment. Notably, this increase correlated well with the improvements in depressive symptoms in the same patients.

Although this study did not actually *measure neurogenesis in vivo*, the selective increase of the dentate gyrus after ECT, and not in other hippocampal subregions, suggests that neurogenesis may be involved as an underlying substrate that could be responsible for the hippocampal plasticity and growth after ECT [130], consistent with related proxies of neurogenesis in this context [131,132] or data showing that increasing other measures of plasticity in the dentate is sufficient to improve depressive-like symptoms [133]. Also other structural, metabolic and diffusivity changes, like angiogenesis, altered connectivity or expansions in glia, may possibly contribute to the observed effects, as discussed before [123,134,135], but this awaits further research. Furthermore, it is not known whether the ECT effect may depend on parallel rises in brain serotonin levels [136] and leaves cognitive flexibility [137] untouched or not. Neither is it known what the role of stress *per se* is regarding the hippocampal volume in depression [138],

but the association of a selective dentate gyrus volume increase with mood improvement in these patients is intriguing.

Thus, assessing ECT responsivity based on the measurements of hippocampal subfield volumes could be an interesting future clinical approach, particularly for stratifying patients before treatment onset [139]. Related MRI modalities such as magnetic resonance spectroscopy [140] (see below) might also be of interest in this respect, as first studies indicate that the increase in the spectroscopic neurogenic signal might be predictive of ECT effects in depressed patients [141].

## 6. Neurogenesis: relevance for hippocampal function and disease

Over the past decades, our understanding of brain plasticity and functions like spatiotemporal and fear-related encoding of memories, has strongly improved due to the discovery that these processes can be modified and/or stabilized by adult neurogenesis, both in the olfactory bulb and within the hippocampal circuitry [8,88,94,99,142]. Aside from the specific molecular regulation of adult neurogenesis [143–147], important for future brain repair approaches, also the regulation of neurogenesis by environmental factors like stress, exercise, inflammatory mediators and microglia, enrichment and learning [66,72,124,148,149] have triggered great interest. The same applies to the possible role of NSCs and neurogenesis in age-related cognitive decline, dementia, epilepsy, and depression [103]; 2018; [150–156, 32,105,109].

Although evidence linking adult hippocampal neurogenesis to *cognitive function and brain disease* in humans has been so far still limited and often indirect, [33] is one of the first who found reductions in Alzheimer's disease and also correlated cognitive status with changes in neurogenesis ante-mortem. Of the 18 subjects studied, 6 patients had an AD diagnosis, the other 12 were controls (6) or MCI cases (6), but surprisingly, all the subjects in the three groups show AD neuropathological hallmarks and there are no subjects with a Braak-Tau 0 stage. Although no correlation was present with the extent of Alzheimer neuropathology in the same patients, [33] do report that the number of DCX + PCNA + cells correlated well with functional changes ante-mortem and interestingly, with presynaptic SNARE proteins.

In addition, Moreno-Jiménez et al., found a sharp decrease in the number of DCX + immature neurons at early stages of AD (Braak-Tau stage I), far before the deposition of senile plaques or neurofibrillary tangles in the dentate gyrus and found a marked correlation between the number of DCX + cells and the amount of Amyloid beta plaques and Tau tangles in the granule cell layer in their cohort of 45 patients, and these authors indicate that the maturation of immature DCX + neurons is blocked at multiple time points in AD patients.

In the human studies, Moreno-Jiménez et al. studied patients at all 6 Braak-Tau stages and found a prominent decrease in the number of DCX + cells in all AD cases already at Braak-Tau stage I, indicating that this decrease may precede alterations in other hippocampal regions. In Tobin et al., the Braak-Tau stages (and, consequently, the advance of the neuropathological features) were not taken into consideration. As end-stage human tissues were studied, it remains so far unknown whether patients with lower Braak stages would have developed into higher stages had the patients lived longer. Also, a temporal order of events is hard to assume with certainty and future studies, using *in vivo* imaging of neurogenesis may for instance help to answer (see below) whether in the Moreno-Jiménez et al. and Tobin et al. studies, neurogenesis was already reduced from an early age onwards and before AD pathology developed, or whether the reduction was a consequence of the emerging amyloid deposition and/or other neuropathological changes in AD, like CA1 cell loss. While the positive correlations in [33], were found in several other brain regions as well and the dentate gyrus specificity and the issue of correlation/causation thus remains unresolved, these papers are the first to suggest a preliminary link between changes in neuroblast and precursor numbers and synaptic plasticity/cognition in human.

Interestingly, the prominent and (early) reduction in neurogenesis observed in Alzheimer brains is consistent with similar correlations in *earlier animal studies* [157–159]. Also, many circuit deficits seen in the early stages of dementia and *cognitive decline* resemble those seen in animals whose neurogenesis has been inhibited using viral or transgenic approaches [100,154,159]. Along the same lines, induced pluripotent stem cells (iPSCs) derived from patients with familial AD exhibit early neurogenic aberrations compared to non-demented controls [160]. Together, these studies suggest that aspects of aging and age-related disease can be modeled in a dish [161], and that, in addition to the physiological decrease in neurogenesis caused by physiological aging, independent mechanisms might drive its additional reduction in AD [162].

In this regard, the inability to distinguish between two similar events in space and time could explain why patients with AD have difficulties remembering specific events or their context correctly, or why patients with PTSD can relive the same traumatic experiences for instance, even though their circumstances have changed. Corroborating these hypotheses, individuals with mild cognitive impairment (being at increased risk of developing AD) and genetically predisposed AD patients exhibit poor performance when tested in pattern separation tasks [115,163–165].

When considering *stimuli for neurogenesis*, exercise has been correlated with cognitive benefits, parallel to an increase in neurogenesis and an elevation of brain-derived neurotrophic factor (BDNF), both in old wildtype mice [166] and in the 5xFAD transgenic mouse model of AD [152,153]. The beneficial effects of exercise on cognition in AD mice could even be mimicked by genetically and pharmacologically inducing neurogenesis, notably together with elevation of BDNF levels and despite the persistence of amyloid pathology [152,153]. A similar rescue of cognition by modulating (aspects of) neurogenesis was observed before in another study on AD mice [154,167]. Based on such preclinical data, increasing neurogenesis, together with BDNF or other neurotrophic factors may represent an interesting strategy to maintain and/or improve cognition in AD.

*Epilepsy* is another disease with a clear link to adult neurogenesis. Newborn neurons are thought to be activated in response to initial cell loss, which may depend on the severity of the initial status epilepticus [168–170]. Likely dependent on seizure severity, the adult-generated cells can develop aberrant morphologies and get miss-wired, thereby disrupting brain circuits and leading to subsequent seizures and potential memory loss [151,171,172]. Also in human epilepsy, changes in neurogenesis markers have been observed postmortem in association with structural abnormalities [248]. In rodent models, preventing or normalizing aberrant neurogenesis was found to modify excitability or cognition in kindling and stroke models [151,173–175]. As epilepsy has been implicated as one of the risk factors for AD [176] as well as for depression and anxiety, it points to a general role for neurogenesis and/or dentate gyrus changes in these disorders.

Finally, neurogenesis is inhibited by *stress*, that forms an important risk factor for psychopathology and also for AD [105,177,109, 62,72,178–180]. Neurogenesis plays for instance an important role in turning off the *stress response* [87,181], while increasing neurogenesis, for instance by exercise, can promote resilience to stress [182,183]. The same applies to antidepressant drugs that can reverse symptoms of stress and depression for which in at least some conditions, neurogenesis is required [106,184]. In fact, if neurogenesis is depleted in rodents, antidepressant drugs do not rescue performance on specific anxiety and depression tests anymore [185,186,108].

In general, many stress-related disorders, including depression and anxiety disorders, and to some extent also aging, have been linked to changes in neurogenesis [89,105,123] and even dentate gyrus volume [127]. Also, the recent studies on neurogenesis in the amygdala and in relation to stress and fear responses are of interest in this respect [6,12,15,16,187,188,249]. Interestingly, in mice, hippocampal NSC populations change not only with age, but also in their responsivity to

stress hormones, such as glucocorticoid hormones [146], indicating a possible link to alterations in the stress axis during aging ([189]; Martin-Suarez et al., 2019).

Other studies in rodents have further shown that neurogenesis as well as dentate gyrus structure and function in rodents can be 'programmed' by stressful experiences, particularly if they occur *early in life* [190–197]. Also, the function and properties of the newborn cells, for instance their responsiveness to positive stimuli such as exercise in adult life [198], may have been altered for life, often in a sex-specific manner [199–201].

Recent findings by [202] are further consistent with such concepts also in humans. They quantified neural progenitor cells (NPCs), granular neurons, glia and dentate gyrus volume in hippocampi of four groups of drug-free, neuropathology-free subjects and compared patients with major depression who committed suicide and control subjects with and without early life stress (before the age of 15). Their results show that resilience to early life stress involved a larger dentate gyrus, whereas a smaller volume with fewer granular neurons and NPCs was found in the depressed/suicide group [202]. Together with related imaging findings [195], this is one of the first anatomical studies indicating that lasting effects of early life stress on neurogenesis and structural hippocampal measures may also be present in humans and in relation to psychopathology.

Clearly, the recent publication of several notable papers surrounding the [27] paper ([28,50,59]; [31,66,70,203,69,16,32,33,67,68,250]) has re-established human neurogenesis as a vibrant and major field, with important implications for cognition and brain disorders. Since the dentate gyrus has now been implicated in at least some of the cognitive deficits associated with AD, future studies may help to understand whether the 'programming' of neurogenesis by early life stress is indeed involved in the vulnerability to develop later psychopathologies [202] or AD [177], and whether this could underlie aspects of 'cognitive reserve' [204].

The concept of 'reserve' is based on the individual variation in vulnerability and resilience for age-related cognitive decline. It stems from observations that, given a comparable pathological load, some individuals perform better than others in cognitive tasks. One hypothesis presumes that depending on the presence of stimulating and challenging conditions during critical periods of brain development and/or early life, a better 'trained' and more 'flexible' brain may emerge with, for instance, more available connections, hubs and/or an enhanced level of overall plasticity. This higher capacity to circumvent the functional consequences of emerging AD neuropathology may then represent a larger 'reserve', that would take longer to deteriorate functionally, which may thereby delay the deleterious consequences that accompany ageing and postpone the age of onset of AD, as discussed recently both from a preclinical and conceptual perspective [177,204,205]. While it is interesting that 'reserve' can now be quantitatively expressed using a neuroimaging approach [206], it awaits to be studied whether such changes indeed involve the DG and/or neurogenesis, if they indeed depend on specific early life conditions, and whether they can also be modified or rescued by adult experiences.

## 7. Future molecular, cellular and imaging approaches

With the growing availability of well-characterized human brain tissues in brain biobanks worldwide, improved and standardized tissue processing and immunocytochemical protocols will help to further answer important research questions from a histological perspective. To fully understand adult neurogenesis, it will be essential to further characterize the neural stem cell and progenitor developmental stages, their molecular determinants as well as the cellular and molecular composition of the neurogenic niche at discrete time points over the lifespan. With the current development of advanced molecular sequencing techniques and the availability of GWAS data and database access, the possibility to characterize neurogenesis in the human brain

at *single-cell or single-nucleus* level becomes very attractive [11].

Specific protocols are already available for rodent material and have allowed us to establish gene expression profiles specific to neuronal precursors or stem cells in the rodent hippocampus (see [207]). Following isolation of the dentate gyrus cell populations, single-cell RNA sequencing (scRNAseq) of the hippocampal niche can be performed and a comprehensive description of all dentate gyrus cells is feasible based on the identification of distinct cell type-specific markers [208]. Already, scRNAseq of the dentate gyrus along with pseudo-time analysis has identified heterogeneous populations of NSCs and NPCs in rodents [208–211]. The implications of these findings for the understanding of NSC activation and adult neurogenesis, and its functional relevance, and whether a comparable diversity of adult hippocampal NSCs exists in the human brain, remain to be determined. Recent, large scale efforts have reported related single-cell molecular changes in human brain and described comprehensive genomic resources in relation to development and disease (see references in [162,212–215];).

Notably, single-nucleus RNA sequencing (snRNAseq), which enables analysis of single nuclei isolated from frozen or fixed tissue and the enrichment of rare, labeled cell populations by fluorescence-activated cell sorting (FACS), points to a spatial diversity of neurogenesis in the adult dentate gyrus in mice [11]. However, confounding factors related to cell type marker specificity may pose specific hurdles to the interpretation of data derived from scRNAseq or snRNAseq rodent studies.

The identification of NSC- and/or NPC-specific transcriptomic markers has proven particularly challenging, often resulting in the inability to distinguish adult NSC clusters in the dentate gyrus from astrocytes or other niche resident cell populations [208,211]. Emerging markers able to better discriminate between adult NSCs and other related cell lineages, like astrocytes, include *Vnn1*, *Hopx*, *Thrsp* and *Id3*, among others [209,216]. Along the same lines, these studies revealed that genes previously presumed to be unique to astrocytes, such as *ApoE*, are highly expressed in adult hippocampal NSCs and can even be used as markers of stemness ([208,211]; see also; <http://linnarssonlab.org/dentate/>). Alluding to putative functional implications of these observations, the ApoE4 isoform constitutes the most prevalent genetic risk of AD, whereas ApoE was recently shown to regulate the functional integration of adult-born hippocampal neurons into the dentate network [217].

Given some of the noticeable technical advantages of snRNAseq over scRNAseq, including reduced dissociation bias, compatibility with frozen and fixed samples, and the elimination of dissociation-induced transcriptional stress responses, together with their comparable transcript detection power in certain tissue preparations [218], it is anticipated that snRNAseq and/or the development of high-definition spatial transcriptomics [219] will pave the way for future studies aimed to understand the functions of human adult hippocampal NSCs. Such studies may shed new light on the developmental stages and transcriptional dynamics of NSCs, progenitors, and their subtypes. Also, by comparing perinatal, juvenile and adult mice, the molecular dynamics and diversity of dentate gyrus cell types could be revealed and shifts in the molecular identity of quiescent and proliferating radial glia vs adult granule cells could be identified and monitored in relation to developmental and chronological age.

Fundamental similarities have already been described for postnatal and adult neurogenesis in the rodent hippocampus [209] and interesting results have been obtained for human brain as well [212,215,220]. Importantly, transcriptomic analyses in human and non-human primate brain tissue and cerebral organoids also revealed certain evolutionary and molecular constraints to orthologous gene expression across species, pointing towards particular human-specific neurogenic traits [221,222].

Together, these findings corroborate previous histological evidence and support a unique role for neurogenesis in human brain specification, physiology and disease. The holistic view of the cellular and molecular complexity in the mammalian brain that emerges from the

recent scRNAseq and snRNAseq studies will enable us to systematically interrogate the molecular and cellular regulators of the hippocampal neurogenic niche upon physiological aging and in neurodegeneration. Appreciating the contribution of distinct cellular populations to the 'fitness' of the niche and understanding the mechanistic underpinnings of the interaction between NSCs, NPCs and other niche residing cells, like microglia and astrocytes, will be of particular importance herein.

Interestingly, NSCs and NPCs have been shown to exert immunomodulatory functions, which they gradually lose upon aging or with disease progression in AD mice [223,224]. Conversely, deficits in hippocampal neurogenesis could be rescued by depletion of microglia in a genetic mouse model of AD [225]. These observations along with the emerging roles of microglia in aging and AD brain, emphasize the need to systematically study the aging or diseased hippocampal niche as a complex multicellular system.

Although several technical and statistical drawbacks still exist, and a side-to-side comparison between scRNAseq and snRNAseq data in human brain tissue is currently pending, existing evidence suggests that the profiles of single cells largely resemble the patterns obtained after sequencing of single nuclei. This allows for profiling of human tissues archived in brain biobanks worldwide, which may help to advance the field as such profiling of newborn cells will allow better characterization of the different types of neuroblasts and their progression through the neurogenic lineage in the human hippocampus. Applying scRNAseq and/or spatial transcriptomics [219] to investigate transcriptome changes in an age range of post-mortem human hippocampi might also help to identify novel specific markers of hippocampal neurogenesis and address aspects of the relative age of the newborn cells and their proportions in the hippocampus at different ages.

More specifically, single-cell interrogation of the aging or diseased adult hippocampal niche in human brain may also allow the dissection of non cell-autonomous senescence- or neurodegeneration-related molecular regulators of adult neurogenesis, adding to the list of neurotrophic factors, proinflammatory stimuli, amyloid beta, systemic cues and others. Moreover, in addition to DCX, PSA-NCAM, SOX-2 or PROX1, these molecular approaches may result in other suitable, and possibly more stable, markers that could be used to uniquely identify and/or selectively label neuronal precursors or young neurons. Particularly with respect to neurodegeneration and given the mechanistic pleiotropy and pathophysiological complexity of neurodegenerative disorders, mapping the scRNAseq data to their functional [215] and spatial [226] context will be crucial, as it can provide invaluable insights into the role of adult neurogenesis in physiological and pathological aging.

On the other side of the spectrum, non-invasive *imaging and biomarker studies* utilizing magnetic resonance spectroscopy (MRS) could help investigate changes in neurogenesis related metabolites in the live human hippocampus in relation to specific challenges, tasks, or disease states. MRS was used before to examine neural stem cells and neurogenesis. In a series of *in vitro* and *in vivo* studies, Manganas et al., [140] showed that, in particular, a lipid-signal is enriched in the human hippocampus *in vivo*. In extensive validation experiments, the authors examined several types of stem and precursor cells, cells undergoing neuronal differentiation, and a variety of post-mitotic cells *in vitro* and found a selective enrichment of a lipid-rich signal in the stem/progenitor population, but not in other cell types such as astrocytes and neurons. Similarly, the changes in lipid signal were of a similar magnitude after ECS stimulation *in vivo* as after histological analysis of the BrdU-positive cells in the postmortem brains of the same animals [140].

Based on these data, the authors hypothesized that the lipid signal is enriched in human neural stem/progenitor cells and would therefore be more abundant in the hippocampus than in other brain regions where these cells do not reside. Indeed, MRS in a cohort of pre-pubertal, post-pubertal and young adults found abundant signal in the hippocampus compared to cortical/white matter. This report received criticism as methodology used to detect the lipid signal required high technical

expertise and was not automated, thus introducing bias from the operator. Moreover, it extracted the signal from a very noisy area of the spectra without *a priori* knowledge on the type of molecule being detected. Over the past decade, however, these criticisms are being addressed and this emerging technology has been making progress toward more robust and automated studies in humans [141,227–229,153,230].

While providing an indirect measure of human neurogenesis *in vivo*, MRS could thus be a valuable tool to study its relation to pattern separation, stress, cognition, mental health and lifestyle and some attempts in that direction have been made [134,155,231,232]. In this respect and in terms of biomarkers, the recent links between stem cell metabolism [233] and fatty acid metabolism are very interesting. Clearly, stem cells utilize a unique source of energy and their energy metabolism likely requires specific lipids. Advanced MRS approaches for the detection of such *in vivo* neurogenic biomarkers will prove to be very valuable. Ultimately, for any measure of hippocampal neurogenesis, it would be informative to combine with measures of functional brain activity.

## 8. Open questions

Looking forward, we can conclude that following yet another dynamic phase in this field's development, the occurrence of adult neurogenesis in the human brain has been (re-)established. Yet, aside from methodological and functional aspects, many open conceptual questions remain. For one, the differences between developmentally-generated and adult-generated newborn cells is relevant as these cells may have quite different properties and capacities [234–237], but are likely hard to distinguish from one another using current histological methods in human brain. Based on rodent studies, many of the newborn cells are adult-generated, but a considerable proportion of the granule neurons present in the adult human hippocampus has likely been generated around birth, while also specific subsets may die [235]. The birth rate of these cells likely decreases with advancing age and at least in rodents, the process of neurogenesis in the developing dentate gyrus undergoes a transformation from the embryonic to the postnatal period around P14, which is coupled with an increase in neural stem cell differentiation towards neuroblasts rather than glia [209] while also complex migratory patterns are seen [237].

The developmental time window of newborn neurons differs between species and most likely also decreases at a different speed during the lifespan of an individual [203]. As these young, presumably still immature, granule neurons have different properties compared to the older and later-born granule cells, and are relatively more numerous early in life, this implies that young granule cells can also make a unique contribution to hippocampal circuits. Relative to the rate of neurogenesis in rodents, newborn neurons in humans may go through a more extended period of *maturation* (order of months), during which time this subset of cells may retain an enhanced plasticity and could serve important functions within the hippocampal network. Whereas the continued addition of new neurons may provide plasticity in adult rodents, the prolonged development of neurons born earlier in life could provide similar levels of plasticity in adult humans without the effort to produce entirely new population of cells (see also [66]).

Another possibility is that granule cells born in adulthood never become truly identical to those born during early development. One function of the early postnatal hippocampal neurogenesis may be the weakening of existing memories and information storage in favor of strengthening the ability to learn new knowledge and to acquire new information through a rapid and continuous generation of large number of new granule neurons. Hence, it will be important to understand to what extent the different populations of newborn cells, born at different ages, may contribute to overall dentate or hippocampal functions, and to what extent they, and the circuitry they reside in, are influenced by the addition of later born adult-generated neurons, and/or emerging pathology.



In the absence of the BrdU or viral-mediated birth-dating approaches, as are traditionally used in animal models, the identification of additional markers or tools may help determine the birth date or age of individual newborn cells in humans. Whether these originate from the single-cell sequencing approaches or from further development and testing of new antibodies, it will be important to develop them for application on human postmortem brain tissues, with all the necessary methodological requirements as discussed above.

Regarding open questions for the field, first and foremost, it is unclear whether human neurogenesis is regulated to the same extent and by the same environmental and molecular factors as those known from rodent studies. Which molecular factors define the neurogenic niche in humans? How is the integration of stem cells into the existing human hippocampal circuitry enabled? Which factors determine their initial and long-term survival? What is their functional role? How can adult-generated neurons modulate hippocampal network functions in humans?

It further remains elusive how neurogenesis, or the lack of it, can contribute to pathologies that originate in, or relate to, the dentate gyrus, from epilepsy to AD? Based on [32], adult neurogenesis appears to be reduced already early in AD, so a better understanding of their (causal) involvement in diseases like cognitive decline and dementia, but also anxiety and major depression, is needed. Does an early decline in neurogenesis reflect an increased disease vulnerability and if so, is the neural stem cell population 'primed' and affected in AD early on? Intriguingly, the N-methyl-D-aspartate receptor antagonist, memantine, which is currently prescribed as an AD medication, has been shown to increase the number of hippocampal NSCs and adult-born neurons in preclinical rodent studies [238,239], providing indirect evidence for the possible benefits of therapeutically targeting adult neurogenesis in AD.

What role does neurogenesis, and its stimulation during critical periods, play in modulating the hippocampal circuit [240] and in building or preserving a cognitive reserve and later resilience to disease? In contrast, exposure to early life stress or early inflammation during critical periods could suppress neurogenesis in a lasting manner and pose a risk for disease development later in life [241]. Can hence an early stimulation of neurogenesis be protective in this respect and would harnessing or restoring neurogenesis before disease onset or during disease progression (in AD, for example) have the potential to enhance the 'fitness of the niche' and of the hippocampal circuitry as a whole? In rodents, recent evidence indicates that adult neurogenesis modulates DG inputs [240], induces global remapping in the dentate gyrus [242] and can protect the hippocampus from neuronal injury following severe seizures [243]. Reversely, early seizure activity depleted NSCs, impairing cognition in an AD model [244].

These, and many other questions are still open, yet intriguing, challenging and exciting. Together with novel experimental approaches, as discussed above, they will help set the stage for a better comprehension and utilization of human hippocampal neurogenesis to its fullest potential, i.e. understanding its contribution to human hippocampal functions and related disorders like depression and dementia.

## Acknowledgements

PJL and CPF are supported by Alzheimer Nederland. CPF is supported by an ERA-NET grant from the EU ERA-NET-NEURON EJTC 2016. ES receives funding from the Alzheimer Association and Fonds Wetenschappelijk Onderzoek – Vlaanderen. MMS is supported by NIH NIGMS1R01 GM120033. We thank Dr. M Llorens-Martín (University of Madrid, Spain) for her valuable input to an earlier version of our manuscript.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.bbr.2019.112458>.

## References

- [1] P.S. Eriksson, E. Perfilieva, T. Björk-Eriksson, A.M. Alborn, C. Nordborg, D.A. Peterson, F.H. Gage, Neurogenesis in the adult human hippocampus, *Nat. Med.* 4 (1998) 1313–1317.
- [2] R. Coras, F.A. Siebzehnrubl, E. Pauli, H.B. Huttner, M. Njunting, K. Kobow, C. Villmann, E. Hahnen, W. Neuhuber, D. Weigel, M. Buchfelder, H. Stefan, H. Beck, D.A. Steindler, I. Blümcke, Low proliferation and differentiation capacities of adult hippocampal stem cells correlate with memory dysfunction in humans, *Brain* 133 (11) (2010) 3359–3372.
- [3] M.A. Curtis, M. Kam, U. Nannmark, M.F. Anderson, M.Z. Axell, C. Wickelso, S. Holtås, W.M. van Roon-Mom, T. Björk-Eriksson, C. Nordborg, J. Frisén, M. Dragunow, R.L. Faull, P.S. Eriksson, Human neuroblasts migrate to the olfactory bulb via a lateral ventricular extension, *Science* 315 (5816) (2007) 1243–1249.
- [4] T.I. Park, H. Monzo, E.W. Mee, P.S. Bergin, H.H. Teoh, J.M. Montgomery, R.L. Faull, M.A. Curtis, M. Dragunow, Adult human brain neural progenitor cells (NPCs) and fibroblast-like cells have similar properties in vitro but only NPCs differentiate into neurons, *PLoS One* 7 (6) (2012) e37742.
- [5] K.L. Spalding, O. Bergmann, K. Alkass, S. Bernard, M. Salehpour, H.B. Huttner, E. Bostrom, I. Westerlund, C. Vial, B.A. Buchholz, G. Possnert, D.C. Mash, H. Druid, J. Frisén, Dynamics of hippocampal neurogenesis in adult humans, *Cell* 153 (2013) 1219–1227.
- [6] P.J. Bernier, A. Bedard, J. Vinet, M. Levesque, A. Parent, Newly generated neurons in the amygdala and adjoining cortex of adult primates, *Proc. Natl. Acad. Sci. U. S. A.* 20 (August (17)) (2002) 11464–11469 99.
- [7] H.A. Cameron, A.G. Dayer, New interneurons in the adult neocortex: small, sparse, but significant? *Biol. Psychiatry* 63 (7) (2008) 650–655.
- [8] D.M. Cummings, J.S. Snyder, M. Brewer, H.A. Cameron, L. Belluscio, Adult neurogenesis is necessary to refine and maintain circuit specificity, *J. Neurosci.* 34 (41) (2014) 13801–13810.
- [9] A. Ernst, K. Alkass, S. Bernard, M. Salehpour, S. Perl, J. Tisdale, G. Possnert, H. Druid, J. Frisén, Neurogenesis in the striatum of the adult human brain, *Cell* 156 (2014) 1072–1083.
- [10] E. Gould, How widespread is adult neurogenesis in mammals? *Nat. Rev. Neurosci.* 8 (6) (2007) 481–488.
- [11] N. Habib, Y. Li, M. Heidenreich, L. Swiech, I. Avraham-Davidi, J.J. Trombetta, C. Hession, F. Zhang, A. Regev, Div-Seq: Single-nucleus RNA-Seq reveals dynamics of rare adult newborn neurons, *Science* 353 (6302) (2016) 925–928.
- [12] D.J. Jhaveri, A. Tedoldi, S. Hunt, R. Sullivan, N.R. Watts, J.M. Power, P.F. Bartlett, P. Sah, Evidence for newly generated interneurons in the basolateral amygdala of adult mice, *Mol. Psychiatry* 23 (March (3)) (2018) 521–532, <https://doi.org/10.1038/mp.2017>.
- [13] C. Klein, W. Jonas, P. Wiedmer, S. Schreyer, L. Akyüz, J. Spranger, R. Hellweg, B. Steiner, High-fat diet and physical exercise differentially modulate adult neurogenesis in the mouse hypothalamus, *Neuroscience* 400 (2019) 146–156.
- [14] C. La Rosa, L. Bonfanti, Brain plasticity in mammals: an example for the role of comparative medicine in the neurosciences, *Front. Vet. Sci.* 5 (2018) 274, <https://doi.org/10.3389/fvets.2018.00274>.
- [15] M.W. Marlatt, I. Philippens, E. Manders, B. Czeh, M. Joels, H. Krugers, P.J. Lucassen, Distinct structural plasticity in the hippocampus and amygdala of the middle-aged common marmoset (*Callithrix jacchus*), *Exp. Neurol.* 230 (2) (2011) 291–301.
- [16] S.F. Sorrells, M.F. Paredes, D. Velmeshev, V. Herranz-Pérez, K. Sandoval, S. Mayer, E.F. Chang, R. Insausti, A.R. Kriegstein, J.L. Rubenstein, J. Manuel Garcia-Verdugo, E.J. Huang, A. Alvarez-Buylla, Immature excitatory neurons develop during adolescence in the human amygdala, *Nat. Commun.* 10 (1) (2019) 2748, <https://doi.org/10.1038/s41467-019-10765-1> Jun 21.
- [17] X.M. Zhang, Y. Cai, Y. Chu, E.Y. Chen, J.C. Feng, X.G. Luo, K. Xiong, R.G. Struble, R.W. Clough, P.R. Patrylo, J.H. Kordower, X.X. Yan, Doublecortin-expressing cells persist in the associative cerebral cortex and amygdala in aged nonhuman primates, *Front. Neuroanat.* 3 (2009) 17, <https://doi.org/10.3389/neuro.05.017.2009> Oct 13.
- [18] Y. Xu, et al., Neurogenesis in the ependymal layer of the adult rat 3rd ventricle, *Exp. Neurol.* 192 (2) (2005) 251–264.
- [19] M.V. Kokoeva, H. Yin, J.S. Flier, Evidence for constitutive neural cell proliferation in the adult murine hypothalamus, *J. Comp. Neurol.* 505 (2) (2007) 209–220.
- [20] D.M. Feliciano, A. Bordey, L. Bonfanti, Noncanonical sites of adult neurogenesis in the mammalian brain, *Cold Spring Harb. Perspect. Biol.* 7 (10) (2015) a018846.
- [21] D.J. Saaltink, B. Håvik, C.S. Verissimo, P.J. Lucassen, E. Vreugdenhil, Doublecortin and doublecortin-like are expressed in overlapping and non-overlapping neuronal cell population: implications for neurogenesis, *J. Comp. Neurol.* 520 (13) (2012) 2805–2823, <https://doi.org/10.1002/cne.23144> Sep 1.
- [22] M. Batailler, et al., DCX-expressing cells in the vicinity of the hypothalamic neurogenic niche: a comparative study between mouse, sheep, and human tissues, *J. Comp. Neurol.* 522 (8) (2014) 1966–1985.
- [23] S. Yoo, S. Blackshaw, Regulation and function of neurogenesis in the adult mammalian hypothalamus, *Prog. Neurobiol.* 170 (2018) 53–66, <https://doi.org/10.1016/j.pneurobio.2018.04.001> Nov.
- [24] A. Ernst, J. Frisén, Adult neurogenesis in humans- common and unique traits in mammals, *PLoS Biol.* 13 (1) (2015) e1002045.
- [25] H. Azari, B.A. Reynolds, In vitro models for neurogenesis, *Cold Spring Harb. Perspect. Biol.* 8 (6) (2016) a021279pii.
- [26] A. Hermann, M. Maisel, S. Liebau, M. Gerlach, A. Kleger, J. Schwarz, K.S. Kim, G. Antoniadi, H. Lerche, A. Storch, Mesodermal cell types induce neurogenesis

- from adult human hippocampal progenitor cells, *J. Neurochem.* 98 (2) (2006) 629–640.
- [27] S.F. Sorrells, M.F. Paredes, A. Cebrian-Silla, K. Sandoval, D. Qi, K.W. Kelley, D. James, S. Mayer, J. Chang, K.I. Augustine, E.F. Chang, A.J. Gutierrez, A.R. Kriegstein, G.W. Mathern, M.C. Oldham, E.J. Huang, J.M. Garcia-Verdugo, Z. Yang, A. Alvarez-Buylla, Human hippocampal neurogenesis drops sharply in children to undetectable levels in adults, *Nature* 555 (2018) 377–381.
- [28] S. Cipriani, I. Ferrer, E. Aronica, G.G. Kovacs, C. Verney, J. Nardelli, S. Khung, A.L. Delezoide, I. Milenkovic, S. Rasika, P. Manivet, J.L. Benifla, N. Deriot, P. Gressens, H. Adle-Biassette, Hippocampal radial glial subtypes and their neurogenic potential in human fetuses and healthy and Alzheimer's disease adults, *Cereb. Cortex* 28 (7) (2018) 2458–2478.
- [29] C.V. Dennis, L.S. Suh, M.L. Rodriguez, J.J. Kril, G.T. Sutherland, Human adult neurogenesis across the ages: an immunohistochemical study, *Neuropathol. Appl. Neurobiol.* 42 (2016) 621–638.
- [30] J.S. Snyder, Questioning human neurogenesis, *Nature* 555 (7696) (2018) 315–316, <https://doi.org/10.1038/d41586-018-02629-3> PubMed PMID: 29542697.
- [31] M. Boldrini, C.A. Fulmore, A.N. Tartt, L.R. Simeon, I. Pavlova, V. Poposka, et al., Human hippocampal neurogenesis persists throughout aging, *Cell Stem Cell* 22 (4) (2018) 589–599.
- [32] E.P. Moreno-Jiménez, M. Flor-García, J. Terreros-Roncal, A. Rábano, F. Cafini, N. Pallás-Bazarrá, J. Ávila, M. Llorens-Martín, Adult hippocampal neurogenesis is abundant in neurologically healthy subjects and drops sharply in patients with Alzheimer's disease, *Nat. Med.* 25 (4) (2019) 554–560.
- [33] M.K. Tobin, K. Musaraca, A. Disouky, A. Shetti, A. Bheri, W.G. Honer, N. Kim, R.J. Dawe, D.A. Bennett, K. Arfanakis, O. Lazarov, Human hippocampal neurogenesis persists in aged adults and Alzheimer's disease patients, *Cell Stem Cell* pii: S1934-5909 (19) (2019) 30207–3.
- [34] H.G. Kuhn, T. Toda, F.H. Gage, Adult hippocampal neurogenesis: a coming-of-age story, *J. Neurosci.* 38 (49) (2018) 10401–10410.
- [35] J. Altman, G.D. Das, Autoradiographic and histological evidence of postnatal hippocampal neurogenesis in rats, *J. Comp. Neurol.* 124 (3) (1965) 319–335.
- [36] S.A. Goldman, F. Nottebohm, Neuronal production, migration, and differentiation in a vocal control nucleus of the adult female canary brain, *Proc. Natl. Acad. Sci. U. S. A.* 80 (April (8)) (1983) 2390–2394.
- [37] F. Nottebohm, Neuronal replacement in adult brain, *Brain Res. Bull.* 57 (6) (2002) 737–749.
- [38] J. Altman, The Discovery of adult mammalian neurogenesis, in: I. Brain, T. Seki, K. Sawamoto, J.M. Parent, A. Alvarez-Buylla (Eds.), *Neurogenesis in the Adult*, Springer, 2011, pp. 3–46.
- [39] M.S. Kaplan, D.H. Bell, Mitotic neuroblasts in the 9-day-old and 11-month-old rodent hippocampus, *J. Neurosci.* 4 (June (6)) (1984) 1429–1441.
- [40] M.F. Eckenhoff, P. Rakic, Nature and fate of proliferative cells in the hippocampal dentate gyrus during the life span of the rhesus monkey, *J. Neurosci.* 8 (August (8)) (1988) 2729–2747.
- [41] P. Rakic, Limits of neurogenesis in primates, *Science*. 227 (4690) (1985) 1054–1056.
- [42] P. Rakic, Adult neurogenesis in mammals: an identity crisis, *J. Neurosci.* 22 (3) (2002) 614–618.
- [43] K. Boekhoorn, M. Joels, P.J. Lucassen, Increased proliferation reflects glial and vascular-associated changes, but not neurogenesis in the presenile Alzheimer hippocampus, *Neurobiol. Dis.* 24 (2016) 1–14.
- [44] M. Boldrini, M.D. Underwood, R. Hen, G.B. Rosoklija, A.J. Dwork, J. John Mann, V. Arango, Antidepressants increase neural progenitor cells in the human hippocampus, *Neuropsychopharmacology* 34 (11) (2009) 2376–2389.
- [45] M. Boldrini, R. Hen, M.D. Underwood, G.B. Rosoklija, A.J. Dwork, J.J. Mann, V. Arango, Hippocampal angiogenesis and progenitor cell proliferation are increased with antidepressant use in major depression, *Biol. Psychiatry* 72 (7) (2012) 562–571.
- [46] M. Boldrini, A.N. Santiago, R. Hen, A.J. Dwork, G.B. Rosoklija, H. Tamir, V. Arango, J. John Mann, Hippocampal granule neuron number and dentate gyrus volume in antidepressant-treated and untreated major depression, *Neuropsychopharmacology* 38 (6) (2013) 1068–1077.
- [47] A. Ekonomou, G.M. Savva, C. Brayne, G. Forster, P.T. Francis, M. Johnson, E.K. Perry, J. Attems, A. Somani, S.L. Minger, C.G. Ballard, Medical research council cognitive function and ageing neuropathology study. Stage-specific changes in neurogenic and glial markers in Alzheimer's disease, *Biol. Psychiatry* 77 (8) (2015) 711–719.
- [48] A. Gatt, H. Lee, G. Williams, S. Thuret, C. Ballard, Expression of neurogenic markers in Alzheimer's disease: a systematic review and meta-transcriptional analysis, *Neurobiol. Aging* 76 (2019) 166–180.
- [49] K. Jin, A.L. Peel, X.O. Mao, L. Xie, B.A. Cottrell, D.C. Henshall, D.A. Greenberg, Increased hippocampal neurogenesis in Alzheimer's disease, *Proc. Natl. Acad. Sci. U. S. A.* 101 (1) (2004) 343–347.
- [50] T.W. Le Maître, G. Dhanabalan, N. Bogdanovic, K. Alkass, H. Druid, Effects of alcohol abuse on proliferating cells, stem/progenitor cells, and immature neurons in the adult human Hippocampus, *Neuropsychopharmacology* 43 (4) (2018) 690–699.
- [51] P.J. Lucassen, M.W. Stumpel, Q. Wang, E. Aronica, Decreased numbers of progenitor cells but no response to antidepressant drugs in the hippocampus of elderly depressed patients, *Neuropharmacology* 58 (6) (2010) 940–949.
- [52] M.W. Marlatt, J. Bauer, E. Aronica, E.S. van Haastert, J.J. Hoozemans, M. Joels, P.J. Lucassen, Proliferation in the Alzheimer hippocampus is due to microglia, not astroglia, and occurs at sites of amyloid deposition, *Neural Plast.* (2014) 693851.
- [53] K.J. Mathews, K.M. Allen, D. Boerrigter, H. Ball, C. Shannon Weickert, K.L. Double, Evidence for reduced neurogenesis in the aging human hippocampus despite stable stem cell markers, *Aging Cell* 16 (5) (2017) 1195–1199.
- [54] E.K. Perry, M. Johnson, A. Ekonomou, R.H. Perry, C. Ballard, J. Attems, Neurogenic abnormalities in Alzheimer's disease differ between stages of neurogenesis and are partly related to cholinergic pathology, *Neurobiol. Dis.* 47 (2) (2012) 155–162.
- [55] G.T. Sutherland, P.J. Sheahan, J. Matthews, C.V. Dennis, D.S. Sheedy, T. McCrossin, M.A. Curtis, J.J. Kril, The effects of chronic alcoholism on cell proliferation in the human brain, *Exp. Neurol.* 247 (2013) 9–18.
- [56] J.R. Epp, C.L. Beasley, L.A. Galea, Increased hippocampal neurogenesis and p21 expression in depression: dependent on antidepressants, sex, age, and anti-psychotic exposure, *Neuropsychopharmacology* 38 (11) (2013) 2297–2306.
- [57] R. Knöth, I. Singec, M. Ditter, G. Pantazis, P. Capetian, R.P. Meyer, V. Horvat, B. Volk, G. Kempermann, Murine features of neurogenesis in the human hippocampus across the lifespan from 0 to 100 years, *PLoS One* 5 (2010) e8809.
- [58] Y.W. Liu, M.A. Curtis, H.M. Gibbons, E.W. Mee, P.S. Bergin, H.H. Teoh, B. Connor, M. Dragunow, R.L. Faull, Doublecortin expression in the normal and epileptic adult human brain, *Eur. J. Neurosci.* 28 (11) (2008) 2254–2265.
- [59] J.Y.W. Liu, M. Matarin, C. Reeves, A.W. McEvoy, A. Miserocchi, P. Thompson, S.M. Sisodiya, M. Thom, Doublecortin-expressing cell types in temporal lobe epilepsy, *Acta Neuropathol. Commun.* 6 (2018) 60.
- [60] J.P. Brown, S. Couillard-Després, C.M. Cooper-Kuhn, J. Winkler, L. Aigner, H.G. Kuhn, Transient expression of doublecortin during adult neurogenesis, *J. Comp. Neurol.* 467 (1) (2003) 1–10.
- [61] J. Dhaliwal, Y. Xi, E. Bruel-Jungerman, J. Germain, F. Francis, D.C. Lagace, Doublecortin (DCX) is not essential for survival and differentiation of newborn neurons in the adult mouse dentate gyrus, *Front. Neurosci.* 11 (January (9)) (2016) 494.
- [62] C.A. Oomen, J.L. Mayer, E.R. de Kloet, M. Joëls, P.J. Lucassen, Brief treatment with the glucocorticoid receptor antagonist mifepristone normalizes the reduction in neurogenesis after chronic stress, *Eur. J. Neurosci.* 26 (December (12)) (2007) 3395–3401.
- [63] R.W. Verwer, A.A. Sluiter, R.A. Balesar, J.C. Baayen, D.P. Noske, C.M. Dirven, J. Wouda, A.M. van Dam, P.J. Lucassen, D.F. Swaab, Mature astrocytes in the adult human neocortex express the early neuronal marker doublecortin, *Brain*. 130 (Pt 12) (2007) 3321–3335.
- [64] M.S.Y. Yeung, M. Djelloul, E. Steiner, S. Bernard, M. Salehpour, G. Possnert, L. Brundin, J. Frisén, Dynamics of oligodendrocyte generation in multiple sclerosis, *Nature* 566 (February (7745)) (2019) 538–542.
- [65] O. Bergmann, J. Liebl, S. Bernard, K. Alkass, M.S. Yeung, P. Steier, W. Kutschera, L. Johnson, M. Landén, H. Druid, K.L. Spalding, J. Frisén, The age of olfactory bulb neurons in humans, *Neuron*. 24 (May (4)) (2012) 634–639, <https://doi.org/10.1016/j.neuron.2012.03.030> 74.
- [66] G. Kempermann, F.H. Gage, L. Aigner, H. Song, M.A. Curtis, S. Thuret, H.G. Kuhn, S. Jessberger, P.W. Frankland, H.A. Cameron, E. Gould, R. Hen, D.N. Abrous, N. Toni, A.F. Schinder, X. Zhao, P.J. Lucassen, J. Frisén, Human adult neurogenesis: evidence and remaining questions, *Cell Stem Cell* S1934-5909 (18) (2018) 30166–8.
- [67] H. Lee, S. Thuret, Adult human hippocampal neurogenesis: controversy and evidence, *Trends Mol. Med.* 24 (6) (2018) 521–522.
- [68] P.J. Lucassen, N. Toni, G. Kempermann, J. Frisén, F.H. Gage, D.F. Swaab, Limits to human neurogenesis—really? *Mol. Psychiatry* (2019), <https://doi.org/10.1038/s41380-018-0337-5>.
- [69] M.F. Paredes, S.F. Sorrells, A. Cebrian-Silla, K. Sandoval, D. Qi, K.W. Kelley, et al., Does adult neurogenesis persist in the human Hippocampus? *Cell Stem Cell* 23 (6) (2018) 780–781.
- [70] A.N. Tartt, C.A. Fulmore, Y. Liu, G.B. Rosoklija, A.J. Dwork, V. Arango, R. Hen, J.J. Mann, M. Boldrini, Considerations for assessing the extent of hippocampal neurogenesis in the adult and aging human brain, *Cell Stem Cell* 23 (6) (2018) 782–783.
- [71] A.-M. Bao, D.F. Swaab, The art of matching brain tissue from patients and controls for postmortem research, *Handbook Clin. Neurol.* 150 (2018) 197–217.
- [72] P.J. Lucassen, C.A. Oomen, E.F. Naninck, C.P. Fitzsimons, A.M. Van Dam, B. Czeh, A. Korosi, Regulation of adult neurogenesis and plasticity by (Early) stress, glucocorticoids, and inflammation, *Cold Spring Harb. Perspect. Biol.* 7 (2015) a021303.
- [73] S. Brummelte, L.A. Galea, Chronic high corticosterone reduces neurogenesis in the dentate gyrus of adult male and female rats, *Neuroscience* 168 (2010) 680–690 PMID: 20406669.
- [74] C.M. McCormick, C.M. Thomas, C.S. Sheridan, F. Nixon, J.A. Flynn, I.Z. Mathews, Social instability stress in adolescent male rats alters hippocampal neurogenesis and produces deficits in spatial location memory in adulthood, *Hippocampus*. 22 (2012) 1300–1312.
- [75] R. Chawana, A. Alagaili, N. Patzke, M.A. Spocter, O.B. Mohammed, C. Kaswera, et al., Microbots appear to have adult hippocampal neurogenesis, but post-capture stress causes a rapid decline in the number of neurons expressing doublecortin, *Neuroscience* 277 (2014) 724–733.
- [76] J.A. Blair, C. Wang, D. Hernandez, S.L. Siedlak, M.S. Rodgers, R.K. Achar, et al., Individual case analysis of postmortem interval time on brain tissue preservation, *PLoS One* 11 (3) (2016) e0151615.
- [77] P. Wester, D.E. Bateman, P.R. Dodd, J.A. Edwardson, J.A. Hardy, A.M. Kidd, R.H. Perry, G.B. Singh, Agonal status affects the metabolic activity of nerve endings isolated from postmortem human brain, *Neurochem. Pathol.* 3 (3) (1985) p169–180.
- [78] C.M. Monoranu, M. Apfelbacher, E. Grünblatt, B. Puppe, I. Alafuzoff, I. Ferrer, S. Al-Saraj, K. Keyvani, A. Schmitt, P. Falkai, J. Schittenhelm, G. Halliday, J. Kril,

- C. Harper, C. McLean, P. Riederer, W. Roggendorf, pH measurement as quality control on human post mortem brain tissue: a study of the BrainNet Europe consortium, *Neuropathol. Appl. Neurobiol.* 35 (3) (2009) 329–337.
- [79] A. Sierra, S. Martín-Suárez, R. Valcárcel-Martín, J. Pascual-Bravo, S.A. Aelvoet, O. Abiega, J.J. Deudero, A.L. Brewster, I. Bernales, A.E. Anderson, V. Baekelandt, M. Maletić-Savatić, J.M. Encinas, Neuronal hyperactivity accelerates depletion of neural stem cells and impairs hippocampal neurogenesis, *Cell Stem Cell* 16 (5) (2015) 488–503.
- [80] I. Blumcke, R. Spreafico, G. Haaker, R. Coras, K. Kobow, C.G. Bien, et al., Histopathological findings in brain tissue obtained during epilepsy surgery, *N. Engl. J. Med.* 377 (17) (2017) 1648–1656.
- [81] E.A. Van Vliet, E. Aronica, A. Vezzani, T. Ravizza, Review: Neuroinflammatory pathways as treatment targets and biomarker candidates in epilepsy: emerging evidence from preclinical and clinical studies, *Neuropathol. Appl. Neurobiol.* 44 (February (1)) (2018) 91–111.
- [82] S.M. Ryan, Y.M. Nolan, Neuroinflammation negatively affects adult hippocampal neurogenesis and cognition: can exercise compensate? *Neurosci. Biobehav. Rev.* 61 (2016) 121–131.
- [83] O. Abiega, S. Beccari, I. Diaz-Aparicio, A. Nadjar, S. Layé, Q. Leyrolle, D. Gómez-Nicola, M. Domerq, A. Pérez-Samartín, V. Sánchez-Zafra, I. Paris, J. Valero, J.C. Savage, C.W. Hui, M. Tremblay, J.J. Deudero, A.L. Brewster, A.E. Anderson, L. Zaldumbide, L. Galbarriatu, A. Marinas, V. Md, C. Matute, M. Maletić-Savatić, J.M. Encinas, A. Sierra, Neuronal hyperactivity disturbs ATP microgradients, impairs microglial motility, and reduces phagocytic receptor expression triggering Apoptosis/Microglial phagocytosis uncoupling, *PLoS Biol.* 14 (5) (2016) e1002466.
- [84] J.M. Encinas, G. Enikolopov, Identifying and quantitating neural stem and progenitor cells in the adult brain, *Methods Cell Biol.* 85 (2008) 243–272.
- [85] H.R. Noori, C.A. Fornal, The appropriateness of unbiased optical fractionators to assess cell proliferation in the adult hippocampus, *Front. Neurosci.* 22 (December (5)) (2011) 140, <https://doi.org/10.3389/fnins.2011.00140>.
- [86] M. Kipp, M.C. Kiessling, T. Hochstrasser, C. Roggenkamp, C. Schmitz, Design-based stereology for evaluation of histological parameters, *J. Mol. Neurosci.* 61 (March (3)) (2017) 325–342.
- [87] C. Anacker, V.M. Luna, G.S. Stevens, A. Millette, R. Shores, J.C. Jimenez, B. Chen, R. Hen, Hippocampal neurogenesis confers stress resilience by inhibiting the ventral dentate gyrus, *Nature* 559 (7712) (2018) 98–102.
- [88] K.A. Huckleberry, F. Shue, T. Copeland, R.A. Chitwood, W. Yin, M.R. Drew, Dorsal and ventral hippocampal adult-born neurons contribute to context fear memory, *Neuropsychopharmacology* 43 (12) (2018) 2487–2496.
- [89] A. Tanti, W.P. Westphal, V. Girault, B. Brizard, S. Devers, A.-M. Leguisquet, A. Surget, C. Belzung, Region-dependent and stage-specific effects of stress, environmental enrichment, and antidepressant treatment on hippocampal neurogenesis, *Hippocampus* 23 (2013) 797–811.
- [90] M.V. Wu, R. Hen, Functional dissociation of adult-born neurons along the dorso-ventral axis of the dentate gyrus, *Hippocampus* 24 (7) (2014) 751–761.
- [91] S. Becker, Neurogenesis and pattern separation: time for a divorce, *Wiley Interdiscip. Rev. Cogn. Sci.* 8 (3) (2017), <https://doi.org/10.1002/wics.1427>.
- [92] C.D. Clelland, M. Choi, C. Romberg, G.D. Clemenson Jr., A. Fragniere, P. Tyers, S. Jessberger, L.M. Saksida, R.A. Barker, F.H. Gage, T.J. Bussey, A functional role for adult hippocampal neurogenesis in spatial pattern separation, *Science* 325 (5937) (2009) 210–213.
- [93] D.M. Curlik 2nd, T.J. Shors, Learning increases the survival of newborn neurons provided that learning is difficult to achieve and successful, *J. Cogn. Neurosci.* 23 (September (9)) (2011) 2159–2170.
- [94] M.R. Drew, K.A. Huckleberry, Modulation of Aversive Memory by Adult Hippocampal Neurogenesis, *Neurotherapeutics.* 14 (3) (2017) 646–661.
- [95] D. Dupret, A. Fabre, M.D. Döbryssa, A. Panatier, J.J. Rodríguez, S. Lamarque, V. Lemaire, S.H. Oliet, P.V. Piazza, D.N. Arous, Spatial learning depends on both the addition and removal of new hippocampal neurons, *PLoS Biol.* 5 (August (8)) (2007) e214.
- [96] D.N. Arous, J.M. Wojtowicz, Interaction between neurogenesis and hippocampal memory system: new vistas, *Cold Spring Harb. Perspect. Biol.* 7 (6) (2015) a018952pii.
- [97] A. Sahay, D.A. Wilson, R. Hen, Pattern separation: a common function for new neurons in hippocampus and olfactory bulb, *Neuron.* 70 (4) (2011) 582–588.
- [98] E. Kropff, S.M. Yang, A.F. Schinder, Dynamic role of adult-born dentate granule cells in memory processing, *Curr. Opin. Neurobiol.* 35 (2015) 21–26.
- [99] D.O. Seo, M.A. Carillo, S. Chih-Hsiung Lim, K.F. Tanaka, M.R. Drew, Adult hippocampal neurogenesis modulates fear learning through associative and non-associative mechanisms, *J. Neurosci.* 35 (32) (2015) 11330–11345.
- [100] S.M. Miller, A. Sahay, Functions of adult-born neurons in hippocampal memory interference and indexing, *Nat. Neurosci.* 22 (10) (2019) 1565–1575.
- [101] A.S. Hill, A. Sahay, R. Hen, Increasing adult hippocampal neurogenesis is sufficient to reduce anxiety and depression-like behaviors, *Neuropsychopharmacology* 40 (10) (2015) 2368–2378.
- [102] J.R. Epp, R. Silva Mera, S. Köhler, S.A. Josselyn, P.W. Frankland, Neurogenesis-mediated forgetting minimizes proactive interference, *Nat. Commun.* 26 (February (7)) (2016) 10838.
- [103] C. Anacker, R. Hen, Adult hippocampal neurogenesis and cognitive flexibility - linking memory and mood, *Nat. Rev. Neurosci.* 18 (6) (2017) 335–346.
- [104] J.S. Snyder, L.R. Glover, K.M. Sanzone, J.F. Kamhi, H.A. Cameron, The effects of exercise and stress on the survival and maturation of adult-generated granule cells, *Hippocampus.* 19 (10) (2009) 898–906.
- [105] B.R. Miller, R. Hen, The current state of the neurogenic theory of depression and anxiety, *Curr. Opin. Neurobiol.* 30 (2015) 51–58.
- [106] C. Anacker, P.A. Zunszain, A. Cattaneo, L.A. Carvalho, M.J. Garabedian, S. Thuret, J. Price, C.M. Pariante, Antidepressants increase human hippocampal neurogenesis by activating the glucocorticoid receptor, *Mol. Psychiatry* 16 (July (7)) (2011) 738–750.
- [107] B.R. Levine, J.F. Cryan, O.F. O'Leary, Role of adult hippocampal neurogenesis in stress resilience, *Neurobiol. Stress* 1 (2014) 147–155.
- [108] A. Surget, A. Tanti, E.D. Leonardo, A. Laugeray, Q. Rainer, C. Touma, R. Palme, G. Griebel, Y. Iburguen-Vargas, R. Hen, C. Belzung, Antidepressants recruit new neurons to improve stress response regulation, *Mol. Psychiatry* 16 (12) (2011) 1177–1188.
- [109] T.J. Schoenfeld, H.A. Cameron, Adult neurogenesis and mental illness, *Neuropsychopharmacology* 40 (1) (2015) 113–128.
- [110] T. Toda, S.L. Parylak, S.B. Linker, F.H. Gage, The role of adult hippocampal neurogenesis in brain health and disease, *Mol. Psychiatry* 24 (1) (2019) 67–87.
- [111] D.J. Creer, C. Romberg, L.M. Saksida, H. van Praag, T.J. Bussey, Running enhances spatial pattern separation in mice, *Proc. Natl. Acad. Sci. U. S. A.* 107 (5) (2010) 2367–2372.
- [112] K.G. Akers, A. Martinez-Canabal, L. Restivo, A.P. Yiu, A. De Cristofaro, H.L. Hsiang, A.L. Wheeler, A. Guskjolen, Y. Niibori, H. Shoji, K. Ohira, B.A. Richards, T. Miyakawa, S.A. Josselyn, P.W. Frankland, Hippocampal neurogenesis regulates forgetting during adulthood and infancy, *Science.* 344 (6184) (2014) 598–602.
- [113] A. Bakker, C.B. Kirwan, M. Miller, C.E. Stark, Pattern separation in the human hippocampal CA3 and dentate gyrus, *Science* 319 (5870) (2008) 1640–1642.
- [114] M.A. Yassa, J.W. Lacy, S.M. Stark, M.S. Albert, M. Gallagher, C.E. Stark, Pattern separation deficits associated with increased hippocampal CA3 and dentate gyrus activity in nondemented older adults, *Hippocampus.* 21 (9) (2011) 968–979.
- [115] S.M. Stark, M.A. Yassa, J.W. Lacy, C.E. Stark, A task to assess behavioral pattern separation (BPS) in humans: data from healthy aging and mild cognitive impairment, *Neuropsychologia.* 51 (12) (2013) 2442–2449.
- [116] M.A. Yassa, C.E. Stark, Pattern separation in the hippocampus, *Trends Neurosci.* 34 (10) (2011) 515–525.
- [117] M. Azab, S.M. Stark, C.E. Stark, Contributions of human hippocampal subfields to spatial and temporal pattern separation, *Hippocampus.* 24 (3) (2014) 293–302.
- [118] T. Das, E.I. Ivleva, A.D. Wagner, C.E. Stark, C.A. Tamminga, Loss of pattern separation performance in schizophrenia suggests dentate gyrus dysfunction, *Schizophr. Res.* 159 (1) (2014) 193–197.
- [119] C. Brock Kirwan, A. Hartshorn, S.M. Stark, N.J. Goodrich-Hunsaker, R.O. Hopkins, C.E. Stark, Pattern separation deficits following damage to the hippocampus, *Neuropsychologia.* 50 (10) (2012) 2408–2414.
- [120] N. Déry, M. Pilgrim, M. Gibala, J. Gillen, J.M. Wojtowicz, G. Macqueen, S. Becker, Adult hippocampal neurogenesis reduces memory interference in humans: opposing effects of aerobic exercise and depression, *Front. Neurosci.* 7 (2013) 66, <https://doi.org/10.3389/fnins.2013.00066>.
- [121] I. Bourdeau, C. Bard, B. Noël, I. Leclerc, M.P. Cordeau, M. Bélaïr, J. Lesage, L. Lafontaine, A. Lacroix, Loss of brain volume in endogenous Cushing's syndrome and its reversibility after correction of hypercortisolism, *J. Clin. Endocrinol. Metab.* 87 (2002) 1949–1954.
- [122] M.N. Starkman, B. Giordani, S.S. Gebarski, S. Berent, M.A. Schork, D.E. Scheingart, Decrease in cortisol reverses human hippocampal atrophy following treatment of Cushing's disease, *Biol. Psychiatry* 46 (1999) 1595–1602.
- [123] P.J. Lucassen, J. Pruessner, N. Sousa, O.F. Almeida, A.M. Van Dam, G. Rajkowska, D.F. Swaab, B. Czeh, Neuropathology of stress, *Acta Neuropathol.* 127 (January (1)) (2014) 109–135.
- [124] C. Vivar, H. van Praag, Running changes the brain: the long and the short of it, *Physiology (Bethesda).* 32 (6) (2017) 410–424.
- [125] K.I. Erickson, M.W. Voss, R.S. Prakash, C. Basak, A. Szabo, L. Chaddock, J.S. Kim, S. Heo, H. Alves, S.M. White, T.R. Wojcicki, E. Mailey, V.J. Vieira, S.A. Martin, B.D. Pence, J.A. Woods, E. McAuley, A.F. Kramer, Exercise training increases size of hippocampus and improves memory, *Proc. Natl. Acad. Sci. U. S. A.* 108 (7) (2011) 3017–3022.
- [126] C.M. Stillman, F. Uyar, H. Huang, G.A. Grove, J.C. Watt, M.E. Wollam, K.I. Erickson, Cardiorespiratory fitness is associated with enhanced hippocampal functional connectivity in healthy young adults, *Hippocampus.* 28 (3) (2018) 239–247.
- [127] J.O. Nuninga, R.C.W. Mandl, M.P. Boks, S. Bakker, M. Somers, S.M. Heringa, W. Nieuwdorp, H. Hoogduin, R.S. Kahn, P. Luijten, I.E.C. Sommer, Volume increase in the dentate gyrus after electroconvulsive therapy in depressed patients as measured with 7T, *Mol. Psychiatry* (2019), <https://doi.org/10.1038/s41380-019-0392-6>.
- [128] M.V. Olesen, G. Wörtwein, J. Folke, B. Pakkenberg, Electroconvulsive stimulation results in long-term survival of newly generated hippocampal neurons in rats, *Hippocampus.* 27 (1) (2017) 52–60.
- [129] J. Jonckheere, J.C. Deloume, G. Dall'igna, N. Chauliac, A. Pelluet, A.S. Ngoun, C. Lentini, J. Brocard, E. Denarier, S. Brugière, Y. Couté, C. Heinrich, C. Porcher, J. Holtzmann, A. Andrieux, M.F. Suaud-Chagny, S. Gory-Fauré, Short- and long-term efficacy of electroconvulsive stimulation in animal models of depression: the essential role of neuronal survival, *Brain Stimul.* 11 (6) (2018) 1336–1347.
- [130] S.H. Joshi, R.T. Espinoza, T. Pirnia, J. Shi, Y. Wang, B. Ayers, A. Leaver, R.P. Woods, K.L. Narr, Structural plasticity of the Hippocampus and amygdala induced by electroconvulsive therapy in major depression, *Biol. Psychiatry* 79 (4) (2016) 282–292.
- [131] J. Krogh, E. Rostrop, C. Thomsen, B. Elfving, P. Videbech, M. Nordentoft, The effect of exercise on hippocampal volume and neurotrophins in patients with major depression—a randomized clinical trial, *J. Affect. Disord.* 165 (2014) 24–30.
- [132] I. Tendolkar, M. van Beek, I. van Oostrom, M. Mulder, J. Janzing, R.O. Voshaar,

- P. van Eijndhoven, Electroconvulsive therapy increases hippocampal and amygdala volume in therapy refractory depression: a longitudinal pilot study, *Psychiatry Res.* 214 (3) (2013) 197–203.
- [133] A. Kazanji, C. Bourcier-Lucas, A. Freysson, D.N. Arous, N. Haddjeri, G. Lucas, Inducing a long-term potentiation in the dentate gyrus is sufficient to produce rapid antidepressant-like effects, *Mol. Psychiatry* 23 (3) (2018) 587–596.
- [134] A. Jorgensen, P. Magnusson, L.G. Hanson, T. Kirkegaard, H. Benveniste, H. Lee, C. Svarer, J.D. Mikkelsen, A. Fink-Jensen, G.M. Knudsen, O.B. Paulsen, T.G. Bolwig, M.B. Jorgensen, Regional brain volumes, diffusivity, and metabolite changes after electroconvulsive therapy for severe depression, *Acta Psychiatr. Scand.* 133 (2) (2016) 154–164.
- [135] B. Czéh, P.J. Lucassen, What causes the hippocampal volume decrease in depression? Are neurogenesis, glial changes and apoptosis implicated? *Eur. Arch. Psychiatry Clin. Neurosci.* 257 (5) (2007) 250–260.
- [136] G. Kronenberg, M. Petermann, C. Dormann, M. Bader, P. Gass, R. Hellweg, F. Klempin, Brain serotonin critically contributes to the biological effects of electroconvulsive seizures, *Eur. Arch. Psychiatry Clin. Neurosci.* 268 (8) (2018) 861–864.
- [137] M. Svensson, M. Graham, J. Ekstrand, P. Höglund, M. Johansson, A. Tingström, Effect of electroconvulsive seizures on cognitive flexibility, *Hippocampus.* 26 (7) (2016) 899–910.
- [138] T.J. Schoenfeld, H.C. McCausland, H.D. Morris, V. Padmanaban, H.A. Cameron, Stress and loss of adult neurogenesis differentially reduce hippocampal volume, *Biol. Psychiatry* 82 (12) (2017) 914–923.
- [139] B. Cao, Q. Luo, Y. Fu, L. Du, T. Qiu, X. Yang, X. Chen, Q. Chen, J.C. Soares, R.Y. Cho, X.Y. Zhang, H. Qiu, Predicting individual responses to the electroconvulsive therapy with hippocampal subfield volumes in major depression disorder, *Sci. Rep.* 8 (1) (2018) 5434.
- [140] L.N. Manganas, X. Zhang, Y. Li, R.D. Hazel, S.D. Smith, M.E. Wagshul, F. Henn, H. Benveniste, P.M. Djuric, G. Enikolopov, M. Maletic-Savatic, Magnetic resonance spectroscopy identifies neural progenitor cells in the live human brain, *Science.* 318 (5852) (2007) 980–985.
- [141] C. Loo, N. Cardoner, H. Hallock, J. Pujol, C. Pantelis, D. Velakoulis, M. Yucel, P. Sachdev, O. Contreras-Rodriguez, M. Urretavizcaya, J. Menchon, C. Suo, P. Djuric, M. Maletic-Savatic, M. Valenzuela, Antidepressant effects of ECT may be related to hippocampal neurogenesis, *Brain Stimulation* 8 (4) (2015) 424–425.
- [142] C. Vivar, H. van Praag, Functional circuits of new neurons in the dentate gyrus, *Neural Circuits* 7 (2013) 15.
- [143] B. Yao, K.M. Christian, C. He, P. Jin, G.L. Ming, H. Song, Epigenetic mechanisms in neurogenesis, *Nat. Rev. Neurosci.* 17 (9) (2016) 537–549.
- [144] L. Stappert, F. Klaus, O. Brüstle, MicroRNAs engage in complex circuits regulating adult neurogenesis, *Front. Neurosci.* 12 (2018) 707.
- [145] M. Schouten, M.R. Buijink, P.J. Lucassen, C.P. Fitzsimons, New neurons in aging brains: molecular control by small non-coding RNAs, *Front. Neurosci.* 6 (2012) 25.
- [146] M. Schouten, P. Bielefeld, L. Garcia-Corzo, E.M.J. Passchier, S. Gradari, T. Jungenitz, M. Pons-Espinal, E. Gebara, S. Martín-Suárez, P.J. Lucassen, H.E. De Vries, J.L. Trejo, S.W. Schwarzscher, D. De Pietri Tonelli, N. Toni, H. Mira, J.M. Encinas, C.P. Fitzsimons, Circadian glucocorticoid oscillations preserve a population of adult hippocampal neural stem cells in the aging brain, *Mol Psych.* (2019), <https://doi.org/10.1038/s41380-019-0440-2>.
- [147] F. Semerci, W.T. Choi, A. Bajic, A. Thakkar, J.M. Encinas, F. Depreux, N. Segil, A.K. Groves, M. Maletic-Savatic, Lunatic fringe-mediated Notch signaling regulates adult hippocampal neural stem cell maintenance, *Elife.* 6 (2017) pii: e24660.
- [148] M. Opendak, E. Gould, Adult neurogenesis: a substrate for experience-dependent change, *Trends Cogn. Sci. (Regul. Ed.)* 19 (3) (2015) 151–161.
- [149] N. Rodríguez-Iglesias, A. Sierra, J. Valero, Rewiring of memory circuits: connecting adult newborn neurons with the help of microglia, *Front. Cell Dev. Biol.* 7 (2019) 24, <https://doi.org/10.3389/fcell.2019.00024>.
- [150] P. Bielefeld, E.A. van Vliet, J.A. Gorter, P.J. Lucassen, C.P. Fitzsimons, Different subsets of newborn granule cells: a possible role in epileptogenesis? *Eur. J. Neurosci.* 39 (1) (2014) 1–11.
- [151] P. Bielefeld, I. Durá, J. Danielewicz, V. Baekelandt, P.J. Lucassen, N.A. Arous, J.M. Encinas, C.P. Fitzsimons, Insult-induced alterations in hippocampal neurogenesis: functional consequences and possible therapeutic strategies, *Behav. Brain Res.* 17 (October (372)) (2019) 112032.
- [152] S.H. Choi, E. Bylykbashi, Z.K. Chatila, S.W. Lee, B. Pulli, G.D. Clemenson, E. Kim, A. Rompala, M.K. Oram, C. Asselin, J. Aronson, C. Zhang, S.J. Miller, A. Lesinski, J.W. Chen, D.Y. Kim, H. van Praag, B.M. Spiegelman, F.H. Gage, R.E. Tanzi, Combined adult neurogenesis and BDNF mimic exercise effects on cognition in an Alzheimer's mouse model, *Science* 361 (6406) (2018).
- [153] W.T. Choi, M. Tosun, H.H. Jeong, C. Karakas, F. Semerci, Z. Liu, M. Maletic-Savatic, Metabolomics of mammalian brain reveals regional differences, *BMC Syst. Biol.* 12 (Suppl. 8) (2018) 127.
- [154] R.F. Dard, L. Dahan, C. Rampon, Targeting hippocampal adult neurogenesis using transcription factors to reduce Alzheimer's disease-associated memory impairments, *Hippocampus.* (November (14)) (2018), <https://doi.org/10.1002/hipo.23052>.
- [155] K. Gandy, S. Kim, C. Sharp, L. Dindo, M. Maletic-Savatic, C. Calarge, Pattern Separation: A Potential Marker of Impaired Hippocampal Adult Neurogenesis in Major Depressive Disorder, *Front. Neurosci.* 11 (2017) 571.
- [156] M. Llorens-Martín, Exercising new neurons to vanquish alzheimer disease, *Brain Plast.* 4 (1) (2018) 111–126.
- [157] O. Wirths, Altered neurogenesis in mouse models of Alzheimer disease, *Neurogenesis Austin (Austin)* 4 (1) (2017) e1327002 May 9.
- [158] C. Hollands, N. Bartolotti, O. Lazarov, Alzheimer's Disease and Hippocampal Adult Neurogenesis; Exploring Shared Mechanisms, *Front. Neurosci.* 10 (2016) 178.
- [159] A. Krezymon, K. Richetin, H. Halley, L. Roybon, J.M. Lassalle, B. Francès, L. Verret, C. Rampon, Modifications of hippocampal circuits and, 2013 Sep Modifications of hippocampal circuits and early disruption of adult neurogenesis in the tg2576 mouse model of Alzheimer's disease, *PLoS One* 27 (September (9)) (2013) e76497 8.
- [160] J. Yang, H. Zhao, Y. Ma, G. Shi, J. Song, Y. Tang, S. Li, T. Li, N. Liu, F. Tang, J. Gu, L. Zhang, Z. Zhang, X. Zhang, Y. Jin, W. Le, Early pathogenic event of Alzheimer's disease documented in iPSCs from patients with PSEN1 mutations, *Oncotarget.* 8 (5) (2017) 7900–7913.
- [161] J. Mertens, D. Reid, Y. Kim, F.H. Gage, Aging in a dish: iPSC-Derived and directly induced neurons for studying brain aging and age-related neurodegenerative diseases, *Annu. Rev. Genet.* 52 (2018) 271–293.
- [162] H. Mathys, J. Davila-Velderrain, Z. Peng, F. Gao, S. Mohammadi, J.Z. Young, M. Menon, L. He, F. Abdurrob, X. Jiang, A.J. Martorell, R.M. Ransohoff, B.P. Hafler, D.A. Bennett, M. Kellis, L.H. Tsai, Single-cell transcriptomic analysis of Alzheimer's disease, *Nature* 570 (June (7761)) (2019) 332–337.
- [163] M.A. Yassa, S.M. Stark, A. Bakker, M.S. Albert, M. Gallagher, C.E. Stark, High-resolution structural and functional MRI of hippocampal CA3 and dentate gyrus in patients with amnesic mild cognitive impairment, *Neuroimage* 51 (3) (2010) 1242–1252.
- [164] B.A. Ally, E.P. Hussey, P.C. Ko, R.J. Molitor, Pattern separation and pattern completion in Alzheimer's disease: evidence of rapid forgetting in amnesic mild cognitive impairment, *Hippocampus.* 23 (12) (2013) 1246–1258.
- [165] K.A. Wesnes, P. Annas, H. Basun, C. Edgar, K. Blennow, Performance on a pattern separation task by Alzheimer's patients shows possible links between disrupted dentate gyrus activity and apolipoprotein E  $\epsilon$ 4 status and cerebrospinal fluid amyloid- $\beta$ 42 levels, *Alzheimers Res. Ther.* 6 (2) (2014) 20.
- [166] M.W. Marlatt, M.C. Potter, P.J. Lucassen, H. van Praag, Running throughout middle-age improves memory function, hippocampal neurogenesis, and BDNF levels in female C57BL/6J mice, *Dev. Neurobiol.* 72 (6) (2012) 943–952.
- [167] K. Richetin, C. Leclerc, N. Toni, T. Gallopin, S. Pech, L. Roybon, C. Rampon, Genetic manipulation of adult-born hippocampal neurons rescues memory in a mouse model of Alzheimer's disease, *Brain* 138 (February (Pt 2)) (2015) 440–455.
- [168] C.T. Ekdahl, C. Zhu, S. Bonde, B.A. Bahr, K. Blomgren, O. Lindvall, Death mechanisms in status epilepticus-generated neurons and effects of additional seizures on their survival, *Neurobiol. Dis.* 14 (December (3)) (2003) 513–523.
- [169] J.A. Gorter, P.M. Gonçalves Pereira, E.A. van Vliet, E. Aronica, F.H. Lopes da Silva, P.J. Lucassen, Neuronal cell death in a rat model for mesial temporal lobe epilepsy is induced by the initial status epilepticus and not by later repeated spontaneous seizures, *Epilepsia.* 44 (5) (2003) 647–658.
- [170] P. Bielefeld, M. Schouten, G.M. Meijer, M.J. Breuk, K. Geijtenbeek, S. Karavel, A. Tiaglik, A.H. Vuuregge, R.A.L. Willems, D. Witkamp, P.J. Lucassen, J.M. Encinas, C.P. Fitzsimons, Co-administration of anti microRNA-124 and -137 oligonucleotides prevents hippocampal neural stem cell loss upon non-convulsive seizures, *Front. Mol. Neurosci.* 12 (2019) 31, <https://doi.org/10.3389/fnmol.2019.00031>.
- [171] J.C. Wood, J.S. Jackson, K. Jakubs, K.Z. Chapman, C.T. Ekdahl, Z. Kokaia, M. Kokaia, O. Lindvall, Functional integration of new hippocampal neurons following insults to the adult brain is determined by characteristics of pathological environment, *Exp. Neurol.* 229 (2011) 484–493, <https://doi.org/10.1016/j.expneurol.2011.03.019>.
- [172] T. Uemori, K. Toda, T. Seki, Seizure severity-dependent selective vulnerability of the granule cell layer and aberrant neurogenesis in the rat hippocampus, *Hippocampus.* 27 (2017) 1054–1068, <https://doi.org/10.1002/hipo.22752>.
- [173] S. Jessberger, J.M. Parent, Epilepsy and adult neurogenesis, *Cold Spring Harb. Perspect. Biol.* 7 (12) (2015) pii:a020677.
- [174] R. Raedt, P. Boon, A. Persson, A.M. Alborn, T. Boterberg, A. Van Dycke, B. Linder, T. De Smedt, W.J. Wadman, E. Ben-Menachem, P.S. Eriksson, Radiation of the rat brain suppresses seizure-induced neurogenesis and transiently enhances excitability during kindling acquisition, *Epilepsia.* 48 (10) (2007) 1952–1963.
- [175] M.I. Cuartero, J. de la Parra, A. Pérez-Ruiz, I. Bravo-Ferrer, V. Durán-Laforet, A. García-Culebras, J.M. García-Segura, J. Dhaliwal, P.W. Frankland, I. Lizasoain, M.Á. Moro, Abolition of aberrant neurogenesis ameliorates cognitive impairment after stroke in mice, *J. Clin. Invest.* (2019), <https://doi.org/10.1172/JCI120412>.
- [176] J.J. Palop, L. Mucke, Network abnormalities and interneuron dysfunction in Alzheimer disease, *Nat. Rev. Neurosci.* 17 (12) (2016) 777–792.
- [177] S.L. Lesuis, L. Hoeijmakers, A. Korosi, S.R. de Rooij, D.F. Swaab, H.W. Kessels, P.J. Lucassen, H.J. Krugers, Vulnerability and resilience to Alzheimer's disease: early life conditions modulate neuropathology and determine cognitive reserve, *Alzheimers Res. Ther.* 10 (1) (2018) 95.
- [178] J. Herbert, P.J. Lucassen, Depression as a risk factor for Alzheimer's disease: genes, steroids, cytokines and neurogenesis - what do we need to know? *Front. Neuroendocrinol.* 41 (2016) 153–171. Apr.
- [179] P. Desmarais, D. Weidman, A. Wassef, M.A. Bruneau, J. Friedland, P. Bajsarowicz, M.P. Thibodeau, N. Herrmann, Q.D. Nguyen, The interplay between post-traumatic stress disorder and dementia: a systematic review, *Am. J. Geriatr. Psychiatry* S1064–7481 (19) (2019) 30469, <https://doi.org/10.1016/j.jagp.2019.08.006> pii: -5 [Epub ahead of print].
- [180] C.M. Escher, L. Sannemann, F. Jessen, Stress and Alzheimer's disease, *J. Neural Transm. Vienna (Vienna)* 126 (9) (2019) 1155–1161.
- [181] J.S. Snyder, A. Soumier, M. Brewer, J. Pickel, H.A. Cameron, Adult hippocampal neurogenesis buffers stress responses and depressive behaviour, *Nature.* 476 (7361) (2011) 458–461.
- [182] T.S. Kannangara, M.J. Lucero, J. Gil-Mohapel, R.J. Drapala, J.M. Simpson, B.R. Christie, H. van Praag, Running reduces stress and enhances cell genesis in

- aged mice, *Neurobiol. Aging* 32 (12) (2011) 2279–2286.
- [183] E. Castilla-Ortega, C. Rosell-Valle, C. Pedraza, F. Rodríguez de Fonseca, G. Estivill-Torrús, L.J. Santín, Voluntary exercise followed by chronic stress strikingly increases mature adult-born hippocampal neurons and prevents stress-induced deficits in 'what-when-where' memory, *Neurobiol. Learn. Mem.* 109 (2014) 62–73.
- [184] D.J. David, B.A. Samuels, Q. Rainer, J.W. Wang, D. Marsteller, I. Mendez, M. Drew, D.A. Craig, B.P. Guiard, J.P. Guilloux, R.P. Artymyshyn, A.M. Gardier, C. Gerald, I.A. Antonijevic, E.D. Leonardo, R. Hen, Neurogenesis-dependent and -independent effects of fluoxetine in an animal model of anxiety/depression, *Neuron*. 62 (4) (2009) 479–493.
- [185] L. Santarelli, M. Saxe, C. Gross, A. Surget, F. Battaglia, S. Dulawa, N. Weisstaub, J. Lee, R. Duman, O. Arancio, C. Belzung, R. Hen, Requirement of hippocampal neurogenesis for the behavioral effects of antidepressants, *Science* 301 (5634) (2003) 805–809.
- [186] A. Surget, M. Saxe, S. Leman, Y. Ibarguen-Vargas, S. Chalou, G. Griebel, R. Hen, C. Belzung, Drug-dependent requirement of hippocampal neurogenesis in a model of depression and of antidepressant reversal, *Biol. Psychiatry* 64 (4) (2008) 293–301.
- [187] M. Piumatti, O. Palazzo, C. La Rosa, P. Crociara, R. Parolisi, F. Luzzati, F. Lévy, L. Bonfanti, Non-Newly Generated, "Immature" Neurons in the Sheep Brain Are Not Restricted to Cerebral Cortex, *J. Neurosci.* 38 (4) (2018) 826–842 Jan 24.
- [188] M.L. Saul, D.L. Helmreich, S. Rehman, J.L. Fudge, Proliferating cells in the adolescent rat amygdala: characterization and response to stress, *Neuroscience*. 311 (2015) 105–117.
- [189] L.E.B. Bettio, L. Rajendran, J. Gil-Mohapel, The effects of aging in the hippocampus and cognitive decline, *Neurosci. Biobehav. Rev.* 79 (August) (2017) 66–86.
- [190] V. Lemaire, M. Koehl, M. Le Moal, D.N. Abrous, Prenatal stress produces learning deficits associated with an inhibition of neurogenesis in the hippocampus, *Proc. Natl. Acad. Sci. U. S. A.* 97 (20) (2000) 11032–11037.
- [191] E.F. Naninck, L. Hoesjmakers, N. Kakava-Georgiadou, A. Meesters, S.E. Lazic, P.J. Lucassen, A. Korosi, Chronic early life stress alters developmental and adult neurogenesis and impairs cognitive function in mice, *Hippocampus*. 25 (3) (2015) 309–328.
- [192] M.H. Teicher, C.M. Anderson, A. Polcari, Childhood maltreatment is associated with reduced volume in the hippocampal subfields CA3, dentate gyrus, and subiculum, *Proc. Natl. Acad. Sci. U. S. A.* 109 (9) (2012) E563–72.
- [193] C.A. Oomen, H. Soeters, N. Audureau, L. Vermunt, F.N. van Hasselt, E.M. Manders, M. Joëls, H. Krugers, P.J. Lucassen, Early maternal deprivation affects dentate gyrus structure and emotional learning in adult female rats, *Psychopharmacology (Berl.)* 214 (1) (2011) 249–260.
- [194] I. Herpfer, H. Hezel, W. Reichardt, K. Clark, J. Geiger, C.M. Gross, A. Heyer, V. Neagu, H. Bhatia, H.C. Atas, B.L. Fiebich, J. Bischofberger, C.A. Haas, K. Lieb, C. Normann, Early life stress differentially modulates distinct forms of brain plasticity in young and adult mice, *PLoS One* 7 (10) (2012) e46004.
- [195] J.L. Luby, D.M. Barch, A. Belden, M.S. Gaffrey, R. Tillman, C. Babb, T. Nishino, H. Suzuki, K.N. Botteron, Maternal support in early childhood predicts larger hippocampal volumes at school age, *Proc. Natl. Acad. Sci. U. S. A.* 109 (8) (2012) 2854–2859.
- [196] R. Ruiz, A. Roque, E. Pineda, P. Licona-Limón, J. José Valdéz-Alarcón, N. Lajud, Early life stress accelerates age-induced effects on neurogenesis, depression, and metabolic risk, *Psychoneuroendocrinology* 96 (2018) 203–211.
- [197] M. Youssef, P. Atsak, J. Cardenas, S. Kosmidis, E.D. Leonardo, A. Dranovsky, Early life stress delays hippocampal development and diminishes the adult stem cell pool in mice, *Sci. Rep.* 9 (1) (2019) 4120 Mar 11.
- [198] M.R. Abbink, E.F.G. Naninck, P.J. Lucassen, A. Korosi, Early-life stress diminishes the increase in neurogenesis after exercise in adult female mice, *Hippocampus*. 27 (8) (2017) 839–844.
- [199] R.S. Eid, J.A. Chaiton, S.E. Lieblich, T.S. Bodnar, J. Weinberg, L.A.M. Galea, Early and late effects of maternal experience on hippocampal neurogenesis, microglia, and the circulating cytokine milieu, *Neurobiol. Aging* 78 (2019) 1–17.
- [200] M. Loi, J.C. Mossink, G.F. Meerhoff, J.L. Den Blaauwen, P.J. Lucassen, M. Joëls, Effects of early-life stress on cognitive function and hippocampal structure in female rodents, *Neuroscience* 342 (2017) 101–119.
- [201] S. Yagi, L.A.M. Galea, Sex differences in hippocampal cognition and neurogenesis, *Neuropsychopharmacology* 44 (1) (2019) 200–213.
- [202] M. Boldrini, H. Galfalvy, A.J. Dwork, G.B. Rosoklija, I. Trencevska-Ivanovska, G. Pavlovski, R. Hen, V. Arango, J.J. Mann, Resilience is associated with larger dentate gyrus, while suicide decedents with major depressive disorder have fewer granule neurons, *Biol. Psychiatry* 85 (10) (2019) 850–862.
- [203] J.S. Snyder, Recalibrating the relevance of adult neurogenesis, *Trends Neurosci.* 42 (3) (2019) 164–178.
- [204] Y. Stern, E.M. Arenaza-Urquijo, D. Bartrés-Faz, S. Belleville, M. Cantilon, G. Chetelat, M. Ewers, N. Franzmeier, G. Kempermann, W.S. Kremen, O. Okonkwo, N. Scarmeas, A. Soldan, C. Udeh-Momoh, M. Valenzuela, P. Vemuri, E. Vuoksima, Reserve, resilience and protective factors PIA empirical definitions and conceptual frameworks workgroup. whitepaper: defining and investigating cognitive reserve, brain reserve, and brain maintenance, *Alzheimers Dement. pii: S1552-5260 (18) (2018) 33491–33495*.
- [205] C. Groot, A.C. van Loenhoud, F. Barkhof, B.N.M. van Berckel, T. Koene, C.C. Teunissen, P. Scheltens, W.M. van der Flier, R. Ossenkoppele, Differential effects of cognitive reserve and brain reserve on cognition in Alzheimer's disease, *Neurology* 90 (2) (2018) e149–e156.
- [206] A.C. Van Loenhoud, A.M. Wink, C. Groot, S.C.J. Verfaillie, J. Twisk, F. Barkhof, B. van Berckel, P. Scheltens, W.M. van der Flier, R. Ossenkoppele, A neuroimaging approach to capture cognitive reserve: application to Alzheimer's disease, *Hum. Brain Mapp.* 38 (9) (2017) 4703–4715.
- [207] J.M. Encinas, C.P. Fitzsimons, Gene regulation in adult neural stem cells. Current challenges and possible applications, *Adv. Drug Deliv. Rev.* 120 (2017) 118–132.
- [208] B. Artergiani, A. Lyubimova, M. Muraro, J.H. van Es, A. van Oudenaarden, H. Clevers, A single-cell RNA sequencing study reveals cellular and molecular dynamics of the hippocampal neurogenic niche, *Cell Rep.* 21 (11) (2017) 3271–3284.
- [209] H. Hochgerner, A. Zeisel, P. Lönnerberg, S. Linnarsson, Conserved properties of dentate gyrus neurogenesis across postnatal development revealed by single-cell RNA sequencing, *Nat. Neurosci.* 21 (February (2)) (2018) 290–299.
- [210] O. Basak, T.G. Krieger, M.J. Muraro, K. Wiebrands, D.E. Stange, J. Frias-Aldeguer, N.C. Rivron, M. van de Wetering, J.H. van Es, A. van Oudenaarden, B.D. Simons, H. Clevers, Troy + brain stem cells cycle through quiescence and regulate their number by sensing niche occupancy, *Proc. Natl. Acad. Sci. U. S. A.* 115 (4) (2018) E610–E619.
- [211] J. Shin, D.A. Berg, Y. Zhu, J.Y. Shin, J. Song, M.A. Bonaguidi, G. Enikolopov, D.W. Nauen, K.M. Christian, G.L. Ming, H. Song, Single-cell RNA-Seq with waterfall reveals molecular cascades underlying adult neurogenesis, *Cell Stem Cell* 17 (3) (2015) 360–372.
- [212] PsychENCODE Consortium, Revealing the brain's molecular architecture, *Science* 362 (6420) (2018) 1262–1263 Dec 14.
- [213] D. Wang, S. Liu, J. Warrell, H. Won, X. Shi, F.C.P. Navarro, et al., Comprehensive functional genomic resource and integrative model for the human brain, *Science* 362 (6420) (2018).
- [214] M. Li, G. Santpere, Y. Imamura Kawasawa, O.V. Evgrafov, F.O. Gulden, S. Pochareddy, et al., Integrative functional genomic analysis of human brain development and neuropsychiatric risks, *Science* 362 (6420) (2018).
- [215] S. Mayer, J. Chen, D. Velmeshev, A. Mayer, U.C. Eze, A. Bhaduri, C.E. Cunha, D. Jung, A. Arjun, E. Li, B. Alvarado, S. Wang, N. Lovegren, M.L. Gonzales, L. Szpankowski, A. Leyrat, J.A.A. West, G. Panagiotakos, A. Alvarez-Buylla, M.F. Paredes, T.J. Nowakowski, A.A. Pollen, A.R. Kriegstein, Multimodal single-cell analysis reveals physiological maturation in the developing human neocortex, *Neuron* 102 (1) (2019) 143–158.
- [216] A. Zeisel, H. Hochgerner, P. Lönnerberg, A. Johnsson, F. Memic, J. van der Zwan, M. Häring, E. Braun, L.E. Borm, G. La Manno, S. Codeluppi, A. Furlan, K. Lee, N. Skene, K.D. Harris, J. Hjerling-Lefler, E. Arenas, P. Ernors, U. Marklund, S. Linnarsson, Molecular architecture of the mouse nervous system, *Cell* 174 (4) (2018) 999–1014 e22.
- [217] Y. Tensaouti, E.P. Stephanz, T.S. Yu, S.G. Kerner, ApoE regulates the development of adult newborn hippocampal neurons, *eNeuro*. 5 (4) (2018) Aug 2 pii: ENEURO.0155-18.2018.
- [218] H. Wu, Y. Kirita, E.L. Donnelly, B.D. Humphreys, Advantages of single-nucleus over single-cell RNA sequencing of adult kidney: rare cell types and novel cell states revealed in fibrosis, *J. Am. Soc. Nephrol.* 30 (January (1)) (2019) 23–32.
- [219] S. Vickovic, G. Eraslan, F. Salmén, J. Klughammer, L. Stenbeck, D. Schapiro, T. Äijö, R. Bonneau, L. Bergensträhle, J.F. Navarro, J. Gould, G.K. Griffin, Å. Borg, M. Ronaghi, J. Frisén, J. Lundberg, A. Regev, P.L. Ståhl, High-definition spatial transcriptomics for in situ tissue profiling, *Nat. Methods* 16 (October (10)) (2019) 987–990.
- [220] R.D. Hodge, T.E. Bakken, J.A. Miller, K.A. Smith, E.R. Barkan, L.T. Graybeck, J.L. Close, B. Long, N. Johansen, O. Penn, Z. Yao, J. Eggertson, T. Höllt, B.P. Levi, S.I. Shehata, B. Aevermann, A. Beller, D. Bertagnolli, K. Brouner, T. Casper, C. Cobbs, R. Dalley, N. Dee, S.L. Ding, R.G. Ellenbogen, O. Fong, E. Garren, J. Goldy, R.P. Gwinn, D. Hirschstein, C.D. Keene, M. Keshk, A.L. Ko, K. Lathia, A. Mahfouz, Z. Maltzer, M. McGraw, T. Nguyen, J. Nyhus, J.G. Ojemann, A. Oldre, S. Parry, S. Reynolds, C. Rimorin, N.V. Shapovalova, S. Somasundaram, A. Szafer, E.R. Thomsen, M. Tieu, G. Quon, R.H. Scheuermann, R. Yuste, S.M. Sunkin, B. Lelieveldt, D. Feng, L. Ng, A. Bernard, M. Hawrylycz, J.W. Phillips, B. Tasic, H. Zeng, A.R. Jones, C. Koch, E.S. Lein, Conserved cell types with divergent features in human versus mouse cortex, *Nature* (August (21)) (2019), <https://doi.org/10.1038/s41586-019-1506-7>.
- [221] Y. Zhu, A.M.M. Sousa, T. Gao, M. Skarica, M. Li, G. Santpere, P. Esteller-Cucala, D. Juan, L. Ferrández-Peral, F.O. Gulden, M. Yang, D.J. Miller, T. Marques-Bonet, Y. Imamura Kawasawa, H. Zhao, N. Sestan, Spatiotemporal transcriptomic divergence across human and macaque brain development, *Science* 362 (6420) (2018) Dec 14.
- [222] A.A. Pollen, A. Bhaduri, M.G. Andrews, T.J. Nowakowski, O.S. Meyerson, M.A. Mostajo-Radji, E. Di Lullo, B. Alvarado, M. Bedolli, M.L. Dougherty, I.T. Fiddes, Z.N. Kronenberg, J. Shuga, A.A. Leyrat, J.A. West, M. Bershteyn, C.B. Lowe, B.J. Pavlovic, S.R. Salama, D. Haussler, E.E. Eichler, A.R. Kriegstein, Establishing cerebral organoids as models of human-specific brain evolution, *Cell* 176 (4) (2019) 743–756 Feb 7 e17.
- [223] J.B. Aimone, Y. Li, S.W. Lee, G.D. Clemenson, W. Deng, F.H. Gage, Regulation and function of adult neurogenesis: from genes to cognition, *Physiol. Rev.* 94 (October (4)) (2014) 991–1026.
- [224] N. Fainstein, N. Dan-Goor, T. Ben-Hur, Resident brain neural precursor cells develop age-dependent loss of therapeutic functions in Alzheimer's mice, *Neurobiol. Aging* 72 (2018) 40–52 Dec.
- [225] S. Ortega-Martinez, N. Palla, X. Zhang, E. Lipman, S.S. Sisodia, Deficits in enrichment-dependent neurogenesis and enhanced anxiety behaviors mediated by expression of alzheimer's disease-linked P51 variants are rescued by microglial depletion, *J. Neurosci.* 39 (34) (2019) 6766–6780. Aug 21.
- [226] S. Jolly, V. Lang, V.H. Koelzer, C.S. Frigerio, L. Magno, P.C. Salinas, P. Whiting, E. Palomer, Single-cell quantification of mRNA expression in the human brain, *Sci. Rep.* 9 (2019) 12353.

- [227] L.H. Ma, Y. Li, P.M. Djurić, M. Maletić-Savatić, Systems biology approach to imaging of neural stem cells, *Methods Mol. Biol.* 711 (2011) 421–434.
- [228] M. Sanz Cortes, A.N. Shetty, N. Park, X. Han, M. Maletić-Savatic, W. Lee, Novel methodologies for MR spectroscopy detection of free lipids associated with neuroprogenitor cells in the human fetal brain in vivo, *Ultrasound Obstet. Gynecol.* 48 (2016) 36.
- [229] W.M.L. Choi, A. Thakkar, S. Gopakumar, K. MacKenzie, M. Maletić-Savatic, Lipid biomarker of neural stem and progenitor cells affects Nr2e1 (tlx) transcriptional activity, *Keystone Symposium on Adult Neurogenesis*, Stockholm, Sweden, 2017.
- [230] C. Calarge, K. Gandy, K.B. Villalobos, J. Nguyen, A. Gregg, S.Y. Kim, M. Maletić-Savatic, In-vivo measurement of a neurogenic signal and pattern separation in adolescent depression, *Neuropsychopharmacology* 42 (2017) S135–S136.
- [231] J.H. Park, H. Lee, R. Makaryus, M. Yu, S.D. Smith, K. Sayed, T. Feng, E. Holland, A. Van der Linden, T.G. Bolwig, G. Enikolopov, H. Benveniste, Metabolic profiling of dividing cells in live rodent brain by proton magnetic resonance spectroscopy (1H MRS) and LCModel analysis, *PLoS One* 9 (5) (2014) e94755.
- [232] C.L. Mallett, D.D. Shuboni-Mulligan, E.M. Shapiro, Tracking neural progenitor cell migration in the rodent brain using magnetic resonance imaging, *Front. Neurosci.* 12 (2019) 995.
- [233] M. Knobloch, S.M. Braun, L. Zurkirchen, C. von Schoultz, N. Zamboni, M.J. Araúzo-Bravo, W.J. Kovacs, O. Karalay, U. Suter, R.A. Machado, M. Roccio, M.P. Lutolf, C.F. Semenkovich, S. Jessberger, Metabolic control of adult neural stem cell activity by Fasn-dependent lipogenesis, *Nature* 493 (7431) (2013) 226–230.
- [234] S.P. Cahill, Green D. Yu RQ, E.V. Todorova, J.S. Snyder, Early survival and delayed death of developmentally-born dentate gyrus neurons, *Hippocampus* 27 (11) (2017) 1155–1167.
- [235] T. Ciric, S.P. Cahill, J.S. Snyder, Dentate gyrus neurons that are born at the peak of development, but not before or after, die in adulthood, *Brain Behav.* 9 (October (10)) (2019) e01435, <https://doi.org/10.1002/brb3.1435> Epub 2019 Oct 1. PubMed PMID: 31576673.
- [236] J.S. Snyder, S.C. Ferrante, H.A. Cameron, Late maturation of adult-born neurons in the temporal dentate gyrus, *PLoS One* 7 (11) (2012) e48757.
- [237] T. Namba, H. Shinohara, T. Seki, Non-radial tortuous migration with cell polarity alterations of newly generated granule neurons in the neonatal rat dentate gyrus, *Brain Struct. Funct.* 224 (2019) 3247–3262.
- [238] T. Namba, M. Maekawa, S. Yuasa, S. Kohsaka, S. Uchino, The Alzheimer's disease drug memantine increases the number of radial glia-like progenitor cells in adult hippocampus, *Glia.* 57 (10) (2009) 1082–1090. Aug 1.
- [239] S.P. Cahill, J.D. Cole, R.Q. Yu, J. Clemans-Gibbon, J.S. Snyder, Differential effects of extended exercise and memantine treatment on adult neurogenesis in male and female rats, *Neuroscience* 390 (2018) 241–255.
- [240] V.M. Luna, C. Anacker, N.S. Burghardt, H. Khandaker, V. Andreu, A. Millette, P. Leary, R. Ravenelle, J.C. Jimenez, A. Mastrodonato, C.A. Denny, A.A. Fenton, H.E. Scharfman, R. Hen, Adult-born hippocampal neurons bidirectionally modulate entorhinal inputs into the dentate gyrus, *Science* 10 (May (6440)) (2019) 578–583 364.
- [241] A. Korosi, E.F. Naninck, C.A. Oomen, M. Schouten, H. Krugers, C. Fitzsimons, P.J. Lucassen, Early-life stress mediated modulation of adult neurogenesis and behavior, *Behav. Brain Res.* 227 (2012) 400–409.
- [242] K.M. McAvoy, K.N. Scobie, S. Berger, C. Russo, N. Guo, P. Decharatanachart, H. Vega-Ramirez, S. Miake-Lye, M. Whalen, M. Nelson, M. Bergami, D. Bartsch, R. Hen, B. Berninger, A. Sahay, Modulating neuronal competition dynamics in the Dentate Gyrus to rejuvenate aging memory circuits, *Neuron.* 91 (6) (2016) 1356–1373.
- [243] S. Jain, J.J. LaFrancois, J.J. Botterill, D. Alcantara-Gonzalez, H.E. Scharfman, Adult neurogenesis in the mouse dentate gyrus protects the hippocampus from neuronal injury following severe seizures, *Hippocampus.* 29 (August (8)) (2019) 683–709.
- [244] C.H. Fu, D.M. Iascone, I. Petrof, A. Hazra, X. Zhang, M.S. Pyfer, U. Tosi, B.F. Corbett, J. Cai, J. Lee, J. Park, L. Iacovitti, H.E. Scharfman, G. Enikolopov, J. Chin, Early seizure activity accelerates depletion of hippocampal neural stem cells and impairs spatial discrimination in an alzheimer's disease model, *Cell Rep.* 27 (13) (2019) 3741–3751, <https://doi.org/10.1016/j.celrep.2019.05.101> e4.
- [245] M.A. Curtis, V.F. Low, R.L. Faull, Neurogenesis and progenitor cells in the adult human brain: a comparison between hippocampal and subventricular progenitor proliferation, *Dev. Neurobiol.* 72 (7) (2012) 990–1005, <https://doi.org/10.1002/dneu.22028>.
- [246] M.A. Curtis, M. Kam, R.L. Faull, Neurogenesis in humans, *Eur. J. Neurosci.* 33 (6) (2011) 1170–1174, <https://doi.org/10.1111/j.1460-9568.2011.07616.x>.
- [247] A. Paul, Z. Chaker, F. Doetsch, Hypothalamic regulation of regionally distinct adult neural stem cells and neurogenesis, *Science* 356 (6345) (2017) 1383–1386, <https://doi.org/10.1126/science.aal3839>.
- [248] C.B. Kirwan, C.E. Stark, Overcoming interference: an fMRI investigation of pattern separation in the medial temporal lobe, *Learn Mem.* 14 (9) (2007) 625–633.
- [249] B.S. McEwen, C. Nasca, J.D. Gray, Stress Effects on Neuronal Structure: Hippocampus, Amygdala, and Prefrontal Cortex, *Neuropsychopharmacology* 41 (1) (2016) 3–23, <https://doi.org/10.1038/npp.2015.171>.
- [250] A.B. Nogueira, M.C. Sogayar, A. Colquhoun, S.A. Siqueira, A.B. Nogueira, P.E. Marchiori, M.J. Teixeira, Existence of a potential neurogenic system in the adult human brain, *J. Transl. Med.* 12 (2014) 75.
- [251] T. Seki, T. Hori, H. Miyata, M. Maehara, T. Namba, Analysis of proliferating neuronal progenitors and immature neurons in the human hippocampus surgically removed from control and epileptic patients, *Sci. Rep.* 9 (1) (2019) 18194, <https://doi.org/10.1038/s41598-019-54684-z>.