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Striatal circuit development and its alterations in Huntington's disease

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Abstract

Huntington's disease (HD) is an inherited neurodegenerative disorder that usually starts during midlife with progressive alterations of motor and cognitive functions. The disease is caused by a CAG repeat expansion within the huntingtin gene leading to severe striatal neurodegeneration. Recent studies conducted on pre-HD children highlight early striatal developmental alterations starting as soon as 6 years old, the earliest age assessed. These findings, in line with data from mouse models of HD, raise the question of when during development do the first disease-related striatal alterations emerge or whether they contribute to the later appearance of the neurodegenerative features of the disease. In this review we will describe the different stages of striatal network development and then discuss recent evidence for its alterations in rodent models of the disease. We argue that a better understanding of the striatum's development should help in assessing aberrant neurodevelopmental processes linked to the HD mutation.

Keywords: striatal development; Huntington's disease; spiny projection neurons; medium spiny neurons; neuronal excitability; striosomes; matrix; basal ganglia.

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I-Introduction

Huntington's disease (HD) is an inherited neurodegenerative disorder affecting around 1 in 10 000 people. This disease is caused by a CAG repeat expansion within the Huntingtin (Htt) gene on chromosome 4 (The Huntington's Disease collaborative research group, 1993). This expansion leads to the translation of a mutated Htt protein (mHtt) with an expanded polyglutamine tract which becomes linked to a cascade of deleterious events leading to progressive alterations of motor and cognitive functions. The appearance of HD symptoms follows three consecutives stages. In the initial early stage, only subtle changes are observed in the form of mood disorders, sleep disturbances, poor motor coordination and cognitive deficits (Julien et al., 2007; Solomon et al., 2007; Wiegand et al., 1991). In the second stage, subjects with HD develop excessive and involuntary movements (chorea) with a deterioration of motor skills (gait, swallowing and speech) and cognitive capacities (decline in thinking and reasoning capacities). Finally, in the third stage, choreic movements are replaced by bradykinesia and rigidity (McColgan and Tabrizi, 2018). There is an accompanying general decline in health and death usually occurs about 15 to 20 years after disease onset. Concerning the neuropathology of the disease, HD is defined by a neurodegeneration of basal ganglia (BG), mainly the striatum, and cortical atrophy.

People with a CAG expansion exceeding 39 repeats will consistently develop HD in midlife, between 30 and 50 years, and the age of onset is inversely related to CAG repeats length (Andrew et al., 1993; Ross and Tabrizi, 2011). Even though the symptomatic phase of the disease with the appearance of serious motor symptoms has a late onset, many studies on premanifest HD patients have reported alterations occurring several years prior to conventional diagnosis. Imaging studies have highlighted changes such as altered brain volume and connectivity, especially in the striatum (Aylward et al., 2011; Harrington et al., 2015; Paulsen et al., 2010), raising the possibility that these early symptoms in HD are due to neurodevelopmental alterations. Indeed, children carrying the HD mutation have a smaller head size, suggesting a deficit in brain growth (Lee et al., 2012). Moreover, two recent neuroimaging studies performed on pre-HD children with a risk of adult-onset HD, showed impairments in striatal development, including striatal hypertrophy as well as hyperconnectivity of cerebellar-striatal circuitry prior to the age of 10 (Tereshchenko et al., 2020; van der Plas et al., 2019). These authors also observed an altered developmental trajectory of striatum growth, with a linear decline in striatal volume in pre-HD children, compared to a non-linear pattern of initial striatal growth (between 6 and 12 years old) and then a volume loss in non-HD children (van der Plas et al., 2019). As these alterations were observed in the earliest age assessed (6 years old), these findings suggest that striatal development could be impaired even earlier. In addition, this idea is in line with molecular and behavioral analyses in mouse models of HD showing early developmental deficits as well as early signs of alterations in several brain structures, including the striatum (Cepeda et al., 2019; Du et al., 2017, 2016; Molero et al., 2009).

Given the obvious difficulties of studying human striatal development and its alterations in HD, and the resultant limited numbers of studies, most of this review will focus

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on research done on rodents. First, we will describe the physiological establishment of the striatal network through development, and second, we will discuss recent evidence showing early impairments of striatal neurodevelopment in mouse models of HD.

II-Overview of striatal network development

The dorsal striatum constitutes the main input structure of the BG network because of its massive innervation by excitatory glutamatergic afferents from the cortex and thalamus. This structure, derived from the embryonic telencephalic vesicle, plays a central role in motor circuit function by sending projections into the BG output nuclei and then onto the thalamus and brainstem via poly-synaptic relays. Moreover, numerous feedback and re-entry loops are involved within this cortex-basal ganglia-thalamus-brainstem motor network so as to promote appropriate motor behaviour according to the context (Kress et al., 2013; Reiner and Deng, 2018). In addition, the operation of the striatum is actively regulated by neuromodulatory afferents, notably dopaminergic and cholinergic inputs from the *substantia nigra pars compacta* (SNc) and the brainstem, respectively, which have been also shown to participate in proper striatal development (Fishell and Van Der Kooy, 1991; Lieberman et al., 2018).

The adult striatum is colonized by two neuronal cell types, namely spiny projection neurons (SPNs) and interneurons. Accounting for approximately 95% of all striatal neurons, SPNs (also known as medium spiny neurons) are GABA-releasing inhibitory neurons with a medium-sized cell body from which branched spiny dendrites radiate (Wilson and Groves, 1980). Striatal interneurons (SINs), known for modulating the activity of SPNs, are aspiny neurons that make up the very small minority of the remaining 5% of striatal neurons. SINs can be divided into two broad classes: large neurons that release acetylcholine as their neurotransmitter, and GABAergic interneurons. In testament to their remarkable heterogeneity, GABAergic SINs can be further subdivided into several subclasses according to their differing molecular, morphological and electrophysiological profiles (Kawaguchi, 1993; Muñoz-Manchado et al., 2018). For a detailed description of the different subpopulations of SINs, refer to two recent reviews (Silberberg and Bolam, 2015; Tepper et al., 2018).

Striatal SPNs follow two distinct, yet complementary, basic organizational plans that define the intrinsic architecture of the striatal network. In terms of the network's functional organization, SPNs are subdivided into two neuronal subtypes according to the output nuclei of the BG to which they project and the molecular markers they express. On one hand, direct pathway SPNs (dSPNs) project monosynaptically to the internal segment of the Globus Pallidus (GPi) and to the *substantia nigra pars reticulata* (SNr) and promote the selection of wanted motor programs (Albin et al., 1989; Freeze et al., 2013). At the molecular level, they express dopamine D1 receptors (D1R) as well as the neuropeptides dynorphin and substance P (SP). On the other hand, indirect pathway SPNs (iSPNs) also target the GPi/SNr complex, but through a poly-synaptic relay, in the external segment of the globus pallidus (GPe), which in turn projects to the subthalamic nucleus (STN; Albin et al., 1989). The activation of these iSPNs promotes the suppression of motor programs (Kravitz et al.,

2010). These neurons carry dopamine D2 receptors (D2R) and release the opioid peptide enkephalin (ENK; Reiner and Anderson, 1990). The maintenance of balance in the excitability and function of these two pathways, which is critical in the execution of controlled movements in time and space, is mainly ensured by dopamine released from SNc neurons. Dopamine helps to increase the excitability of the direct pathway (Lahiri and Bevan, 2020) and decrease that of the indirect pathway in order to facilitate proper voluntary motor skills (Planert et al., 2013).

The second organizational scheme of mature striatal architecture, which is superimposed upon the first, corresponds to the striatum's division into two neurochemically distinct compartments, namely the striosomes, similar to small cellular islands and also called patches, and the surrounding matrix (Graybiel and Ragsdale, 1978; Jain et al., 2001). μ-opioid receptors (MOR) and calbindin are markers of striosomes and matrix, respectively (Gerfen et al., 1985; Pert et al., 1976). The size of the matrix is significantly larger than that of the striosomal compartment, such that a 4:1 ratio is usually observed. These two anatomically distinct compartments are colonized by both dSPNs and iSPNs. Furthermore, within each compartment, dSPNs and iSPNs are fully intermingled, giving rise to a cellular mosaic that is essential for maintaining a functional balance in striatal activity (Tinterri et al., 2018). Striosome and matrix SPNs have been shown to be part of functionally-distinct network and so to be involved in diverse functions. Indeed, the former mainly receive inputs from the prelimbic cortex (Gerfen, 1989; Kincaid and Wilson, 1996) as well as from several midbrain regions and project in particular onto SNc dopaminergic neurons (Crittenden and Graybiel, 2011; Gerfen et al., 1985; Jimenez-Castellanos and Graybiel, 1987; McGregor et al., 2019; Watabe-Uchida et al., 2012). On the other hand, matrix SPNs receive massive inputs from the motor cortex and thalamus (Gerfen, 1989, 1984; Kincaid and Wilson, 1996) and in turn communicate synaptically with the basal ganglia output nuclei (Watabe-Uchida et al., 2012). As a result, striosomes seem to be preferentially involved in evaluation functions for decision-making as well as in motivational behaviours (Friedman et al., 2015), whereas the matrix compartment, in contrast, promotes motor task execution (Flaherty and Graybiel, 1994). Thus, the striosome/matrix compartmentalization is a crucial organizational plan as it defines output and input connectivity of the striatal network, as well as its different functions.

The developmental origins as well as the relationship between these two striatal organization schemes (striosome/matrix compartmentalization and SPNs specification into dSPNs and iSPNs) remain elusive. However, knowledge of this normal physiological situation is of paramount importance to better understanding and eventually confronting the neurodevelopmental abnormalities observed in HD. Thus, we propose here firstly to review the current state of knowledge in the literature concerning the proper embryonic and postnatal development of the striatal network.

1) Mechanisms underlying striosome/matrix compartmentalization and SPN specification

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In mammals, the dorsal striatum is derived from the embryonic ventral telencephalon, which contains the lateral ganglionic eminence (LGE) (***Figure 1A***). The LGE, which forms at embryonic day 9.5 (E9.5), is an intense neurogenic zone containing a pool of neural epithelial (NE) progenitor cells in the ventricular region. These NE cells first give birth to cells which send projections into the subventricular region of the LGE and thus shape radial glia. The latter are the radial glial (RG) cells from which all SPNs originate (Sousa and Fishell, 2010). The same pool of RG cells then differentiate sequentially into two distinct subpopulations of intermediate progenitors (IP) during striatal neurogenesis, first into apical (aIP) then into basal IP (bIP) cells, although the link between these two types of neuronal progenitors and the two SPN subpopulations has not yet been established (Pilz et al., 2013; Turrero García and Harwell, 2017) (***Figure 1B***). Indeed, this lack is why our understanding of the mechanisms underlying the assembly of the embryonic striatal architecture and consequently its functional input and output connectivity is currently so sparse.

To address this question, Kelly and co-workers have recently traced the developmental trajectory of LGE RG cells in mice up until the ultimate stage of their differentiation into SPNs by genetic fate mapping (Kelly et al., 2018). In this study of major interest, the authors highlighted the existence of a developmental program integrated within these neural cells, which runs sequentially in time and space in two major phases: an early phase extending from ~E10 to ~E12.5 during which the pool of RG cells is restricted to the production of aIPs that in turn give rise almost exclusively to striosomal SPNs, and a later and longer phase beginning at ~E13 and ending at ~E17, which generates almost all matrix SPNs, from the same pool of RG cells after an intermediate differentiation step into bIPs (***Figure 1B***) (Kelly et al., 2018). Thus, these results are in line with those of previous studies demonstrating that striosomal and matrix striatogenesis occur sequentially, with the former preceding the latter (Mason et al., 2005; Newman et al., 2015; van der Kooy and Fishell, 1987). Moreover, a differential gene expression profile is associated with each cell type. NE cells express the transcription factor (TF) GS homeobox 1/2 (Gsx1/2), while RG cells express Gsx1/2 and the TF Tis21 ($Gsx1/2^{+}$/$Tis21^{+}$). Regarding IP cells, two neurogenic factors appearing sequentially during striatal neurogenesis allows aIPs from bIPs to be distiguished. Specifically, aIPs express the TF achaete-scute family bHLH 1 (Ascl1) but not the TF distal-less homeobox 1 (Dlx1) ($Ascl1^{+}$/$Dlx1^{-}$), whereas bIPs express both ($Ascl1^{+}$/$Dlx1^{+}$) (***Figure 1B***). This sequential gene expression is proposed to be involved in the chronological production of the two SPN subtypes, where Dlx1 would act downstream from Ascl1 within the bIPs to give rise to matrix SPNs (Kelly et al., 2018; Martín-Ibáñez et al., 2012; Yun et al., 2002). In contrast, the molecular mechanisms underlying this biphasic differentiation of RG cells into aIPs and then into bIPs remains an open question and requires further studies.

In parallel with, but independently from, the developmental program defining striosome/matrix compartmentalization, many other transcriptomic programs are activated in these same IPs, downstream from Ascl1 and Dlx1, to induce SPN neurogenic specification into dSPNs and iSPNs. The identity of direct pathway neurons is specified by three main TFs, namely Insulin gene enhancer protein Islet-1, Early B-Cell Factor (Ebf1) and SRY-Box

Transcription Factor 8 (Sox8), which are expressed as early as E11 and required for the proper development and survival of these neurons (***Figure 1B***). More broadly, these factors ensure the normal development of the direct projection pathway by promoting the development of embryonic and early postnatal functional striatonigral connectivity (Ehrman et al., 2013; Garel et al., 1999; Lobo et al., 2008, 2006; Lu et al., 2014; Merchan-Sala et al., 2017). Regarding Ebf1 specifically, this TF has been shown to be involved in the proper differentiation of matrix compartment dSPNs (Lobo et al., 2008, 2006). For its part, the TF SP9 is instrumental for the normal development of indirect pathway neurons by driving the striatopallidal progenitor differentiation into iSPNs and also by participating in ensuring the survival of these post-mitotic differentiated neurons (***Figure 1B***) (Xu et al., 2018; Zhang et al., 2016). While dSPNs and iSPNs are derived from both aIPs and bIPs, as are striosomal and matrix SPNs, respectively, the relationship between the developmental origins of these two organizational schemes remains to be understood. Nonetheless, several hypotheses have been proposed, including one according to which the aIPs and bIPs sub-groups could exist within these (striosomal/matrix) subpopulations, some of which being committed to generating dSPNs and others to producing iSPNs (Kelly et al., 2018). To confirm this hypothesis, however, more detailed studies on the specific fate of these neural precursor subpopulations are necessary.

Despite a substantial literature on the molecular profile of the developing striatum, a core issue remains to be deciphered, namely the SPN migratory processes that shape the striatal mosaic. Following their specification in the LGE subventricular zone (SVZ), both dSPNs and iSPNs migrate alongside the radial glia towards the mantle zone to integrate the different compartments under formation (early migration towards the striosomes and later migration towards the surrounding matrix). Within the striatal mantle, dSPNs and iSPNs then actively intermix to shape the mosaic cell architecture that is vital for the striatum's function. While it is commonly accepted that SPNs migrate radially to colonize the entire striatum (Halliday and Cepko, 1992; Hamasaki et al., 2003; Song and Harlan, 1994), this assumption has recently been questioned. Indeed, by analyzing the iSPN migration profile within the embryonic striatum by two-photon time-lapse imaging, Tinterri and co-workers revealed that after the early specification of dSPNs/iSPNs, iSPNs gradually invade the striatal mantle, laterally and then medially, by a dSPN-dependent tangential and multidirectional migration (***Figure 1B***) (Tinterri et al., 2018). However, this type of migration, characteristic of MGE-derived interneurons, a neuronal population specified later during striatal neurogenesis (Kelly et al., 2018; Marin et al., 2000; Nóbrega-Pereira et al., 2008), is also common to other LGE- and MGE-derived neuronal populations such as globus pallidus neurons (Dodson et al., 2015; Nóbrega-Pereira et al., 2010). Thus tangential migration is thought to actively participate in the intermixing of dSPNs and iSPNs within both compartments, in association with the classical radial migration profile of dSPNs (Hagimoto et al., 2017; Tinterri et al., 2018). The mechanisms governing this iSPN migration pattern are still unknown. However, Ebf1 would appear to play an important role in this process as its inactivation leads to an altered dSPN/iSPN intermixing (Tinterri et al., 2018). This therefore implies that although the specification of these two neuronal subtypes is largely independent, their intermixing within

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the different compartments is conditioned by the proper development of both dSPNs and iSPNs, which cooperate and interact together to shape a mature and functional striatal network. Another TF, Forkhead box P1 (FoxP1), which is expressed in both dSPNs and iSPNs, could also be involved in this migration process since it has recently been shown to be necessary for the correct migration of iSPNs generated during the early phase of striatogenesis (i.e. those cells intended to colonize the striosome compartment)(Anderson et al., 2020).

Embryonic striatal development involves a critical period during which the shaping of striatal circuitry takes place. This developmental window brings into play a host of specification, migration and interaction processes as well as numerous transcriptomic programs, all tightly regulated in time and space. An abnormal development of this architecture will subsequently have adverse consequences for proper postnatal striatal maturation, which could lead years later to the appearance of debilitating pathologies, as is the case in HD whose pathogenesis is increasingly being thought to comprise a neurodevelopmental component (Cepeda et al., 2019; Humbert, 2010; Kerschbamer and Biagioli, 2016).

2) Postnatal maturation of the striatal circuit

After the embryonic proliferation and migration of the SPNs, the early postnatal period is crucial as it is defined by the establishment of striatal inputs and output connectivity as well as the maturation of SPN properties. Regarding their outputs, it has been shown that striosomal SPNs send their projections toward the SN as early as E17, while matrix SPNs do so only during the first postnatal week (***Figure 2A, C***) (Fishell and van der Kooy, 1989, 1987). In addition, during the first postnatal week, the striatum normally undergoes a physiological cell death period. In rats, between PND2 and PND7, around 30% of striatal neurons die independently of their location in the striosomes or matrix suggesting that their birthdate has no impact on their subsequent survival. However, it has been shown that striatal neurons that have already sent projections to the SN or the GPe at PND2 survive more during this cell death period, suggesting that the development of early striatofugal axons ensures SPN survival (Fishell and Van Der Kooy, 1991).

The postnatal maturation of SPNs is also strongly related to the establishment of their dopaminergic, cortical and thalamic inputs. Dopaminergic innervation is the earliest to develop, with SNc neurons sending their axonal projections to the striatum as soon as E14, although their terminals release dopamine only around E18-PND0, suggesting that most nigrostriatal synapses are functional at birth (***Figure 2A, C***) (Ferrari et al., 2012; Voorn et al., 1988). Dopamine release was shown to be crucial for the maturation of dSPNs as the lack of nigrostriatal dopaminergic transmission prevents the decrease in dSPNs excitability (Lieberman et al., 2018). In parallel, cortical neurons send their axonal projections to the striatum from PND3 (Sohur et al., 2014) but only 75% of SPNs respond to cortical stimulation between PND3 and PND6, indicative of ongoing corticostriatal synaptogenesis (Krajeski et al., 2019). From PND9, all SPNs receive cortical innervation and these excitatory inputs

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continue to develop progressively, especially between PND10 and PND18 suggesting an ongoing strengthening of corticostriatal synapses (***Figure 2B-C***) (Krajeski et al., 2019; Peixoto et al., 2016). Cortex and striatum development appear to be strongly interdependent as an alteration in either striatal or cortical activity during this period has a strong impact on corticostriatal connectivity (Kozorovitskiy et al., 2012; Peixoto et al., 2016). Finally, thalamic neurons send their projections from at least by PND3 as 75% of SPNs respond to a thalamic stimulation at this stage, but the establishment of thalamo-striatal synapses could start even earlier as VGLUT2-positive axons are already found at birth in the striatum (Nakamura et al., 2005). Similarly to the cortical inputs, all SPNs receive thalamic inputs from PND9 and the amplitude of these inputs increase progressively until PND28, also suggesting a continued strengthening of thalamostriatal synapses (Krajeski et al., 2019). As described earlier, striosomal and matrix striatogenesis occur sequentially, with an early production and migration of striosomal SPNs followed by matrix ones (see § II.1.). Consequently, these striosomal SPNs are more susceptible to receiving early inputs from cortex, thalamus and SNc. Indeed, early-forming dopaminergic innervation of the striatum occurs first in the patch compartment before its expansion into the matrix (Edley and Herkenham, 1984; Fishell and van der Kooy, 1989; Graybiel, 1984; Prager and Plotkin, 2019). Similarly, early cortical and thalamic innervation labeling by Vglut1 and Vglut2, respectively, appear to match with the striosomes' location (Nakamura et al., 2005).

Regarding SPN morphology and excitability, it has been shown that during the first postnatal week, neonatal SPNs express immature characteristics as indicated by an absence or slight presence of dendritic spines as well as the presence of thin and varicose dendrites (***Figure 2B-C***) (Sharpe and Tepper, 1998). In terms of their electrophysiological properties, SPNs exhibit immature patterns of activity compared to the adult state, with a lower level of spontaneous activity *in vivo*, and an hyperexcitability observed both *in vivo* and *ex vivo* (Dehorter et al., 2011; Krajeski et al., 2019; Tepper and Trent, 1993). This elevated intrinsic excitability of immature neurons during development, which found in many brain structures and across many species, has been shown to be crucial to developmental processes such as neuronal growth and synapse formation (Spitzer, 2006). After the first postnatal week, SPNs undergo a maturation to attain their adult-like activity state and morphology. Regarding morphology, this maturation involves the development of the dendritic arbor and the formation of dendritic spines, with their density increasing gradually especially between PND10 and PND12 (***Figure 2B-C***). SPN activity also increases from P10, with an overall increase in spontaneous firing rate and burst frequency observed *ex vivo* (Krajeski et al., 2019; Peixoto et al., 2016). Conversely, the intrinsic excitability of SPNs progressively decreases caused by an hyperpolarization of their resting membrane potential and a longer latency to spike firing (higher rheobase and action potential threshold seen *ex vivo*) (Dehorter et al., 2011; Krajeski et al., 2019; Peixoto et al., 2016). This change in excitability is essentially due to the acquisition of inwardly rectifying potassium channel (Kir) currents (Krajeski et al., 2019; Tepper et al., 1998). During this critical PND10-PND12 period, the AMPA/NMDA receptor ratio starts to increase, resulting in a bias towards AMPA receptor recruitment, which is usually related to synapse maturation (Krajeski et al., 2019; Peixoto et

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al., 2016; Petralia et al., 1999). By the end of the fourth postnatal week (PND28), SPNs have morphological and electrophysiological properties that closely resemble those of adult neurons.

Thus, during the postnatal period between PND0 and PND28, SPNs undergo a strong maturation in their morphologies, electrophysiological properties and synaptic wiring (Dehorter et al., 2012, 2011). This maturation involves several mechanisms that occur concomitantly and are interdependent. From PND35, the striatal network appears to be fully mature, concurrently with mouse sexual maturity (Krajeski et al., 2019).

III-Huntingtin plays a key role in striatal development

1) Huntingtin is ubiquitous and involved in many key cellular processes

Htt is a widely distributed protein with a higher expression in the central nervous system than in peripheral tissues. Its expression occurs very early during embryonic development and is maintained throughout adulthood (Bhide et al., 1996; Landwehrmeyer et al., 1995; Marques Sousa and Humbert, 2013; Nasir et al., 1995). Htt is known to be expressed throughout the brain, including the cortex and striatum, although its precise distribution during development is still unknown. Wild-type Htt protein interacts with a large number of partners with which it forms complexes and regulates many cellular functions (Shirasaki et al., 2012). Among these processes, wild-type Htt regulates vesicular trafficking of organelles along microtubules, cell division by controlling the assembly and orientation of the mitotic spindle, the transcription of many key genes such as p53 and also ciliogenesis (for a detailed description of these Htt-regulated cellular processes, see Cattaneo et al., 2005; Saudou and Humbert, 2016).

At the cortico-striatal circuit level, which is primarily affected and dysfunctional in HD, Htt plays a vital role since it promotes striatal neuron survival by regulating several mechanisms. Htt initially stimulates cortical synthesis of the brain-derived neurotrophic factor (BDNF) gene by positively regulating its transcription and then promotes its anterograde vesicular transportation to cortico-striatal synapses as well as its release into the synaptic cleft. In a second step, once BDNF binds to the Tropomyosin receptor kinase B (TrkB) receptor located on the dendrites of post-synaptic striatal neurons, the activated BDNF-TrkB complex is then endocytosed and retrogradely delivered to the somata of these neurons under the action of Htt to activate pro-survival signaling pathways (Gauthier et al., 2004; Liot et al., 2013; Zuccato et al., 2001). Furthermore, it has been shown that Htt exerts this neuroprotective function by repressing caspases-3 and -9-mediated apoptosis (Rigamonti et al., 2001; Zhang et al., 2006). However, while the impact of theHD mutation on the functional integrity of the adult striatum has been widely analyzed, much less is known about the importance of wild-type Htt in normal striatal architecture establishment. The following section thus reviews current knowledge about Htt's involvement throughout striatal development.

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2) Huntingtin is crucial for the cytoarchitectural organization of striatal circuitry

Several studies, in which deletion of wild-type Htt during development was performed, have enabled a better understanding of the multiple functions of the protein in the developing brain and especially in the striatum to be obtained. First, it has been shown that Htt is crucial for normal embryonic development as its homozygous deletion induces an early mortality of mouse embryos (Duyao et al., 1995; Nasir et al., 1995; Zeitlin et al., 1995). Moreover in mice with disrupted Htt from a later embryonic stage (E15), progressive alterations in subsequent adulthood are observed, including neurodegeneration in the striatum, motor deficits, and early mortality, thereby recapitulating impairments found in the HD phenotype (Dragatsis et al., 2000). Second, analyses of chimeric embryos have suggested that Htt is essential for neuronal survival in the striatum (Reiner et al., 2001). Third, in mice with a specific deletion of Htt in Gsx2 lineages (lineage described § II.1 and figure 1B), similar striatal neurodegeneration and motor deficits are observed (Mehler et al., 2019). These latter findings have also been confirmed by a recent study in which a specific deletion of the protein in SPNs was performed (Burrus et al., 2020). The deletion of Htt in iSPNs leads to a dramatic reduction of GABAergic synapses in the GPe, associated with an hyperactivity, in 2 month-old mice. Conversely, the deletion of Htt in dSPNs leads to an increased inhibition of the SNr with an associated hypoactivity in mice at the same age. These results therefore suggest that Htt is required for the maintenance of basal ganglia circuit integrity. Moreover, this specific deletion of Htt induces HD-like alterations in adulthood, evidenced by SPN loss, motor alterations, and reactive gliosis observed in 10 month-old mice (Burrus et al., 2020).

Together these findings suggest that the adult alterations are caused, at least in part, by the loss of function of the protein during the earlier developmental period. However, as Htt is normally reduced or depleted constantly throughout life, the results obtained in the above studies could also be due to the continuous loss of the protein's function. To address this possibility, a recent paper studied the specific role of Htt during neural development by reducing Htt expression prematurely, from embryonic stages until PND21 (Arteaga-Bracho et al., 2016). This experiment induced striatal developmental alterations with ectopic tissue masses observed in the striatum both in the embryo and postnatal stages. In the embryonic stage, the cells within these masses expressed both SPN progenitor markers, Isl1 and Ctip2, and interneurons only one, Nkx2.1. In addition, at PND10 these cells expressed both calbindin and μ-opioid receptors, which are specific markers of matrix and striosomes, respectively. These results indicated that the loss of Htt induces early deficits in the specification, migration and organization of striatal circuitry, thereby underlining the crucial role Htt plays in striatal development. Moreover, the same progressive HD-like phenotype is observed in the adult stage, with striatal neurodegeneration and astrogliosis as well as motor deficits (gait disturbances and motor coordination alterations) occurring. These latter results therefore suggest that a loss of Htt during neural development is also involved in the neurodegeneration observed in later life. These findings are also consistent with studies on induced pluripotent stem cells (iPSCs) from HD patients in culture, which revealed a

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deregulation of genes such as Ctip2, DARPP-32 and Isl1 involved in striatal development (Conforti et al., 2018; Ring et al., 2015; The HD iPSC Consortium, 2017; for review: Wiatr et al., 2018). One explanation proposed is that the lack of Htt during development increases the subsequent vulnerability of striatal neurons to cell death (Arteaga-Bracho et al., 2016; Mehler and Gokhan, 2001). This idea is consistent with the role of Htt in striatal neuron survival through its actions on cortico-striatal pathways (see § III.1.). Finally, it has been shown that a deletion of Htt in the developing cortex leads to an aberrant increase in cortico-striatal synapse formation and SPN dendritic spine maturation, suggesting that cortical Htt is important for negatively regulating synaptic connectivity between the cortex and striatum (McKinstry et al., 2014).

All these studies in which Htt expression levels have been manipulated therefore shed light on the functions of the protein with respect to the development of the striatum. Importantly, Htt appears to be crucial for the correct cytoarchitectural organization of striatal circuitry into striosomes and matrix.

IV-Evidence for abnormal striatal neurodevelopment in mouse models of HD

During the last decade, few studies have provided lines of evidence on the neurodevelopmental aspect of HD. Several characteristics of striatal development appear to be impaired in HD mice models. A first study using Htt-Q111 mice as a model of HD showed alterations in different steps of striatal development from embryonic SPN specification to striatal organization (Molero et al., 2009). In this transgenic line, spatio-temporal striatal neurogenesis is altered with a delayed cell cycle exit of striatal IPs leading to reduced number of striatal NeuN+ neurons at E17.5. This delay in turn impacts on physiological neurogenesis and the formation of early striosomal and matrix cells. Moreover, the volume of progenitor cells appears enhanced and most of these cells express abnormal morphologies with irregular and invaginated nuclei. As a consequence, this abnormal specification profoundly affects the striatal cytoarchitecture in the postnatal period with the expression of the striosomal marker, μ-opioid receptor, being reduced at PND2 whereas the matrix marker, calbindin, displays an altered mosaic pattern at PND7. These defects were only observed in the striatum, suggesting a specific altered maturation and enhanced vulnerability of striatal neurons (Molero et al., 2009). In this context, it is noteworthy that *in vitro* analyses of induced pluripotent stem cells derived from HD patients (Mathkar et al., 2019) or human embryonic stem cells bearing the HD mutation (Ruzo et al., 2018) also display delayed progenitor differentiation as well as an increased volume of progenitors cells with abnormal morphologies. Moreover, in zQ175 mice, the maturation of striatal dendritic spines appears to be accelerated at PND21 without any significant change in either cortical or thalamic striatal synapse numbers (McKinstry et al., 2014). However, in Q140 mice, the number of VGLUT2-positive axodendritic thalamic terminals is decreased by 40% in the striatum at 1 month compared to wild-type mice (Deng et al., 2013). These studies thus suggest that striatal circuit maturation is impaired in a dynamic and complex manner during the first post-natal weeks. Interestingly, a recent study has shown that a selective expression of mHtt only

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during development, from the embryonic phase to PND21, is sufficient to induce an HD-like phenotype in later adult stages, specifically involving striatal neurodegeneration, motor coordination impairments, altered corticostriatal connectivity and striatal electrophysiological activity changes (Molero et al., 2016). Together these findings are therefore consistent with the conclusion that the Htt mutation induces developmental changes that will, in part, lead to the progressive neurodegenerative features of the disease.

V-Concluding remarks / Future directions

The various studies discussed in this review highlight the complexity of the striatum's normal development as well as the deleterious effects of a loss of wild-type Htt function or Htt mutation on striatal development and HD pathogenesis (Burrus et al., 2020; Lopes et al., 2016). Indeed, strong alterations in striatal cytoarchitectural and corticostriatal connectivity are observed when Htt expression is decreased. Similarly, the expression of mHtt induces a delayed specification of striatal progenitors resulting in striatal network modification. Moreover, both low levels of Htt or the expression of mHtt restricted to the embryonic and early postnatal period, when striatal neurogenesis occurs, are sufficient to induce an HD-like phenotype in adulthood. These observations suggest that striatal developmental alterations induced by the loss of Htt function enhance the vulnerability to cell death of striatal neurons and lead to neurodegeneration and motor alterations later in life. Clearly, a better understanding of the specific mechanisms underlying such disruptions of striatal development is needed before realistic attempts can be made to reverse these processes and potentially avoid the neurodegenerative features observed in later life.

Since a striatal hypertrophy was observed in human studies on pre-HD children (van der Plas et al., 2019), it would be interesting to determine whether striatal neuron numbers are also increased in HD mice models during the early postnatal period. As mentioned earlier, during the first postnatal week, the striatum undergoes a cell death period during which 30% of striatal neurons die. Therefore, it is possible that the number of striatal neurons dying during this period is reduced in the HD-phenotype, leading to a striatal hypertrophy. Moreover, it was shown that striatal neurons with already projecting striatofugal axons survive more during this cell death period (Fishell and Van Der Kooy, 1991). It is tempting to hypothesize that the striatal hypertrophy observed in humans is due to an enhanced maturation of striatal neurons that project their striatofugal axons earlier. Consequently, it could also be instructive to look at a possible precocious establishment of striatofugal outputs in mice models of HD during the embryonic and postnatal periods.

The different aspects discussed in this review reinforce the conclusion that the neurodevelopmental aspect of HD should be considered in HD treatments. Given the paucity of studies both in HD patients and rodent models of HD, further investigations are needed to confirm results already obtained and to shed new light on the mechanisms leading to striatal development defects.

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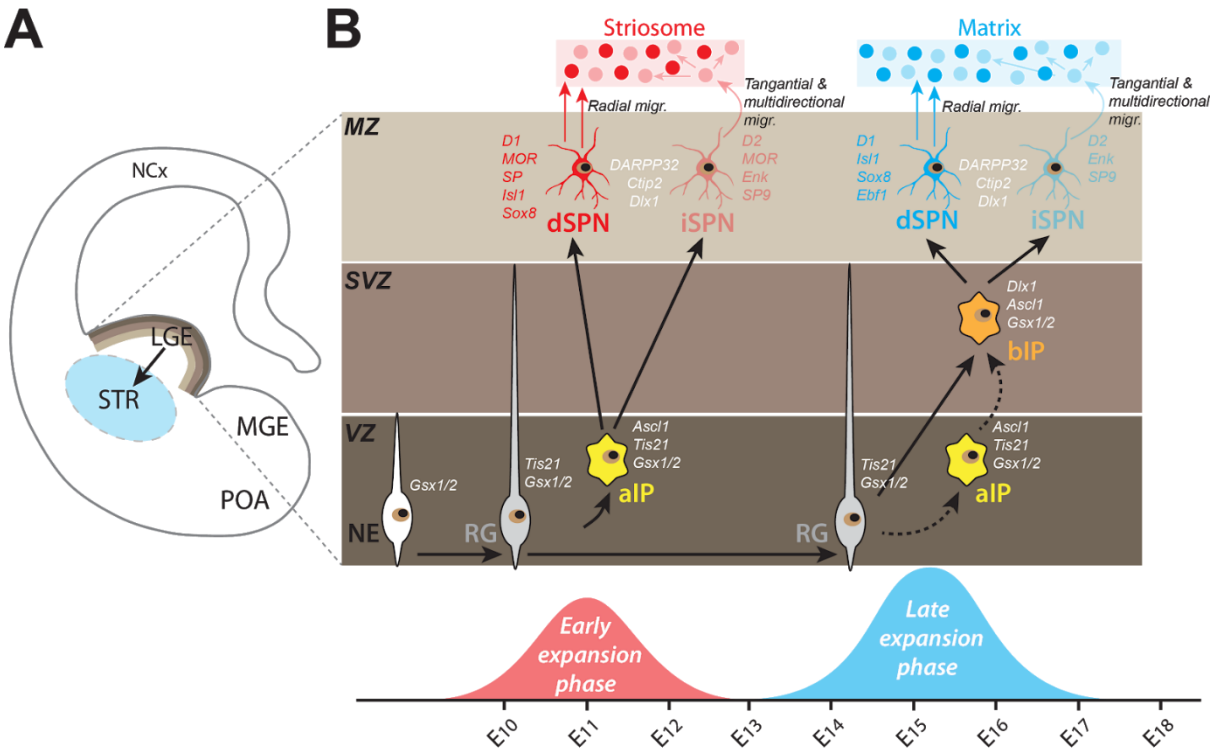

Figure 1: Current model of embryonic mechanisms underlying striatal architecture and the ontogenesis of SPNs. A: Schematic representation of a coronal hemisection of the developing brain in which are represented the neocortex (NCx), striatum (STR), lateral ganglionic eminence (LGE), medial ganglionic eminence (MGE) and the preoptic area (POA). **B**: Enlargement of the LGE region indicating the different expansion phases of neuroepithelial (*NE*) cells leading to the formation of striosomal and matrix striatal compartments. In the early (E10-E12.5) expansion phase, NE cells give rise to radial glial (RG) cells that generate apical intermediate precursors (*aIP*), which in turn give rise to striosomal dSPNs and iSPNs. A second wave of expansion takes place between E13 and E17, during which RG cells give rise directly or indirectly through *aIP* (dashed arrows) to basal intermediate precursors (*bIP*) which will produce matrix dSPNs and iSPNs. While striosomal and matrix dSPNs eventually reach their final destination in the developing striatum following radial migration, iSPNs reach their targets through a tangential and multidirectional migration process.

The molecular identity of the different neuronal progenitors is indicated by the expression of transcription factors (*Gsx1/2; Tis21; Ascl1; Dlx1*), whereas the molecular identity of mature striosomal and matrix SPNs appears in red and blue, respectively.

En: embryonic day n; MZ: mantle zone; SVZ: subventricular zone; VZ: ventricular zone.

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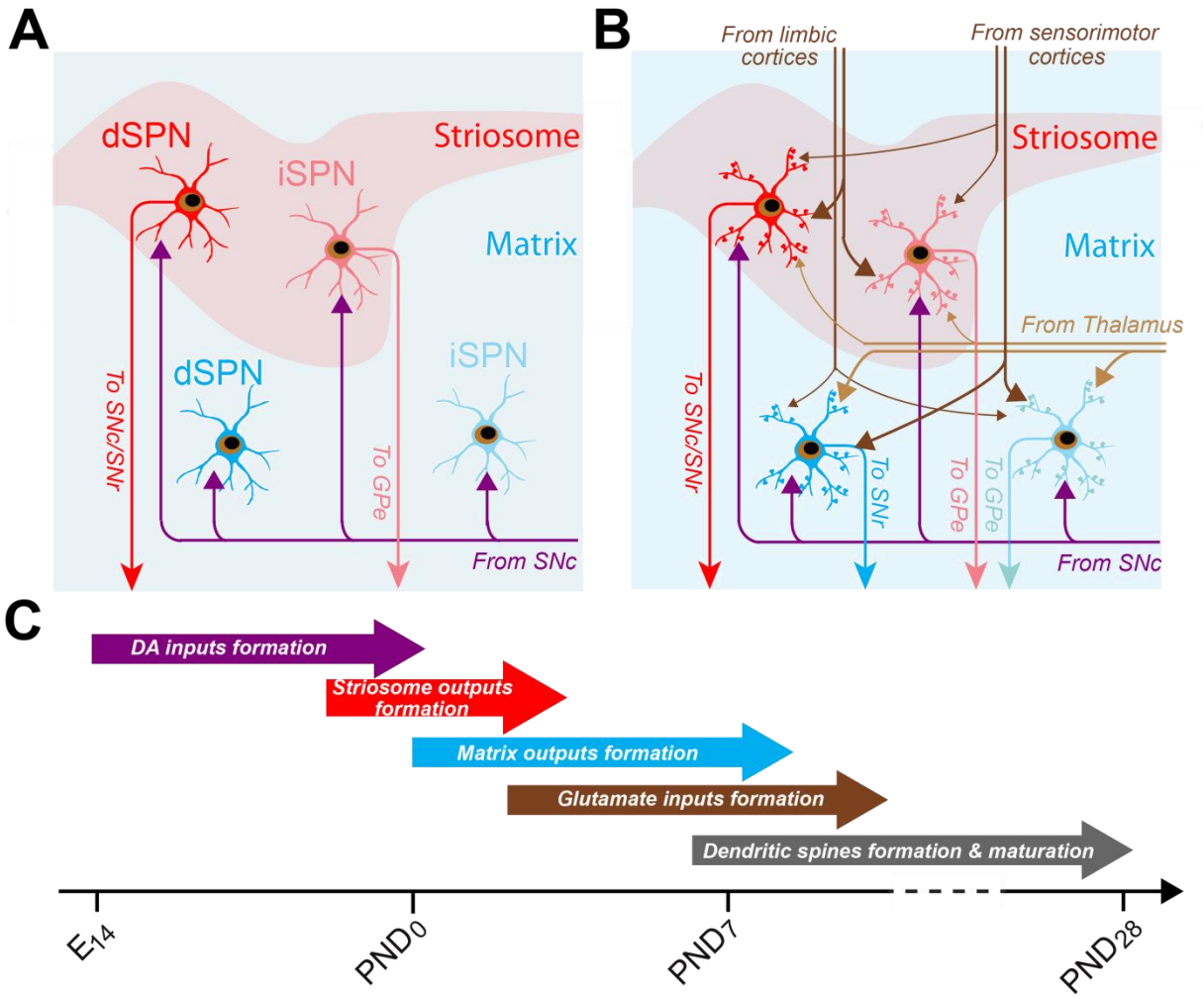

Figure 2: Establishment and maturation of the developing striatum. A-B: Schematics depicting the sequential maturation of the striatum**. A:** Dopaminergic inputs and axonal projections of striosomal SPNs develop principally between E14 and birth (PND0). **B:** During the first postnatal week, matrix SPNs make connections with their targets (the SNr and the GPe) and glutamatergic inputs from the cortex and thalamus are formed. Between the first and fourth postnatal weeks, the striatal microcircuit becomes fully functional with a strengthening of glutamatergic inputs and the formation and maturation of SPN dendritic spines. **C:** Timeline showing the different key steps involved in the maturation of the developing striatum.

En: embryonic day n; GPe: external globus pallidus; PNDn: postnatal day n; SNc: *substantia nigra pars compacta*; SNr: *substantia nigra pars reticulata*.

VI- References

Albin, R.L., Young, A.B., Penney, J.B., 1989. The functional anatomy of basal ganglia disorders. Trends Neurosci. 12, 366–375. https://doi.org/10.1016/0166-2236(89)90074-X

Anderson, A.G., Kulkarni, A., Harper, M., Konopka, G., 2020. Single-Cell Analysis of Foxp1-Driven Mechanisms Essential for Striatal Development. Cell Rep. 30, 3051-3066.e7. https://doi.org/10.1016/j.celrep.2020.02.030

Andrew, S.E., Paul Goldberg, Y., Kremer, B., Telenius, H., Theilmann, J., Adam, S., Starr, E., Squitieri, F., Lin, B., Kalchman, M.A., Graham, R.K., Hayden, M.R., 1993. The relationship between trinucleotide (CAG) repeat length and clinical features of Huntington's disease. Nat. Genet. 4, 398–403. https://doi.org/10.1038/ng0893-398

Arteaga-Bracho, E.E., Gulinello, M., Winchester, M.L., Pichamoorthy, N., Petronglo, J.R., Zambrano, A.D., Inocencio, J., De Jesus, C.D., Louie, J.O., Gokhan, S., Mehler, M.F., Molero, A.E., 2016. Postnatal and adult consequences of loss of huntingtin during development: Implications for Huntington's disease. Neurobiol. Dis. 96, 144–155. https://doi.org/10.1016/j.nbd.2016.09.006

Aylward, E.H., Nopoulos, P.C., Ross, C.A., Langbehn, D.R., Pierson, R.K., Mills, J.A., Johnson, H.J., Magnotta, V.A., Juhl, A.R., Paulsen, J.S., the PREDICT-HD Investigators and Coordinators of the Huntington Study Group, 2011. Longitudinal change in regional brain volumes in prodromal Huntington disease. J. Neurol. Neurosurg. Psychiatry 82, 405–410. https://doi.org/10.1136/jnnp.2010.208264

Bhide, P.G., Day, M., Sapp, E., Schwarz, C., Sheth, A., Kim, J., Young, A.B., Penney, J., Golden, J., Aronin, N., DiFiglia, M., 1996. Expression of normal and mutant huntingtin in the developing brain. J. Neurosci. Off. J. Soc. Neurosci. 16, 5523–5535.

Burrus, C.J., McKinstry, S.U., Kim, N., Ozlu, M.I., Santoki, A.V., Fang, F.Y., Ma, A., Karadeniz, Y.B., Worthington, A.K., Dragatsis, I., Zeitlin, S., Yin, H.H., Eroglu, C., 2020. Striatal Projection Neurons Require Huntingtin for Synaptic Connectivity and Survival. Cell Rep. 30, 642-657.e6. https://doi.org/10.1016/j.celrep.2019.12.069

Cattaneo, E., Zuccato, C., Tartari, M., 2005. Normal huntingtin function: an alternative approach to Huntington's disease. Nat. Rev. Neurosci. 6, 919–930. https://doi.org/10.1038/nrn1806

Cepeda, C., Oikonomou, K.D., Cummings, D., Barry, J., Yazon, V., Chen, D.T., Asai, J., Williams, C.K., Vinters, H.V., 2019. Developmental origins of cortical hyperexcitability in Huntington's disease: Review and new observations. J. Neurosci. Res. jnr.24503. https://doi.org/10.1002/jnr.24503

Conforti, P., Besusso, D., Bocchi, V.D., Faedo, A., Cesana, E., Rossetti, G., Ranzani, V., Svendsen, C.N., Thompson, L.M., Toselli, M., Biella, G., Pagani, M., Cattaneo, E., 2018. Faulty neuronal determination and cell polarization are reverted by modulating HD early phenotypes. Proc. Natl. Acad. Sci. 115, E762–E771. https://doi.org/10.1073/pnas.1715865115

Crittenden, J.R., Graybiel, A.M., 2011. Basal Ganglia Disorders Associated with Imbalances in the Striatal Striosome and Matrix Compartments. Front. Neuroanat. 5. https://doi.org/10.3389/fnana.2011.00059

Dehorter, N., Michel, F.J., Marissal, T., Rotrou, Y., Matrot, B., Lopez, C., Humphries, M.D., Hammond, C., 2011. Onset of pup locomotion coincides with loss of NR2C/D-mediated cortico-striatal EPSCs and dampening of striatal network immature activity. Front. Cell. Neurosci. 5. https://doi.org/10.3389/fncel.2011.00024

Dehorter, N., Vinay, L., Hammond, C., Ben-Ari, Y., 2012. Timing of developmental sequences in different brain structures: physiological and pathological implications: Brain developmental sequences in health and disease. Eur. J. Neurosci. 35, 1846–1856. https://doi.org/10.1111/j.1460-9568.2012.08152.x

Deng, Y.P., Wong, T., Bricker-Anthony, C., Deng, B., Reiner, A., 2013. Loss of corticostriatal and thalamostriatal synaptic terminals precedes striatal projection neuron pathology

in heterozygous Q140 Huntington's disease mice. Neurobiol. Dis. 60, 89–107. https://doi.org/10.1016/j.nbd.2013.08.009

Dodson, P.D., Larvin, J.T., Duffell, J.M., Garas, F.N., Doig, N.M., Kessaris, N., Duguid, I.C., Bogacz, R., Butt, S.J.B., Magill, P.J., 2015. Distinct developmental origins manifest in the specialized encoding of movement by adult neurons of the external globus pallidus. Neuron 86, 501–513. https://doi.org/10.1016/j.neuron.2015.03.007

Dragatsis, I., Levine, M.S., Zeitlin, S., 2000. Inactivation of Hdh in the brain and testis results in progressive neurodegeneration and sterility in mice. Nat. Genet. 26, 300–306. https://doi.org/10.1038/81593

Du, Z., Chazalon, M., Bestaven, E., Leste-Lasserre, T., Baufreton, J., Cazalets, J.-R., Cho, Y.H., Garret, M., 2016. Early GABAergic transmission defects in the external globus pallidus and rest/activity rhythm alteration in a mouse model of Huntington's disease. Neuroscience 329, 363–379. https://doi.org/10.1016/j.neuroscience.2016.05.027

Du, Z., Tertrais, M., Courtand, G., Leste-Lasserre, T., Cardoit, L., Masmejean, F., Halgand, C., Cho, Y.H., Garret, M., 2017. Differential Alteration in Expression of Striatal GABAAR Subunits in Mouse Models of Huntington's Disease. Front. Mol. Neurosci. 10, 198. https://doi.org/10.3389/fnmol.2017.00198

Duyao, M.P., Auerbach, A.B., Ryan, A., Persichetti, F., Barnes, G.T., McNeil, S.M., Ge, P., Vonsattel, J.P., Gusella, J.F., Joyner, A.L., 1995. Inactivation of the mouse Huntington's disease gene homolog Hdh. Science 269, 407–410. https://doi.org/10.1126/science.7618107

Edley, S.M., Herkenham, M., 1984. Comparative development of striatal opiate receptors and dopamine revealed by autoradiography and histofluorescence. Brain Res. 305, 27–42. https://doi.org/10.1016/0006-8993(84)91116-8

Ehrman, L.A., Mu, X., Waclaw, R.R., Yoshida, Y., Vorhees, C.V., Klein, W.H., Campbell, K., 2013. The LIM homeobox gene Isl1 is required for the correct development of the striatonigral pathway in the mouse. Proc. Natl. Acad. Sci. 110, E4026–E4035. https://doi.org/10.1073/pnas.1308275110

Ferrari, D.C., Mdzomba, B.J., Dehorter, N., Lopez, C., Michel, F.J., Libersat, F., Hammond, C., 2012. Midbrain dopaminergic neurons generate calcium and sodium currents and release dopamine in the striatum of pups. Front. Cell. Neurosci. 6. https://doi.org/10.3389/fncel.2012.00007

Fishell, G., Van Der Kooy, D., 1991. Pattern formation in the striatum: Neurons with early projections to the substantia nigra survive the cell death period. J. Comp. Neurol. 312, 33–42. https://doi.org/10.1002/cne.903120104

Fishell, G., van der Kooy, D., 1989. Pattern formation in the striatum: developmental changes in the distribution of striatonigral projections. Dev. Brain Res. 45, 239–255. https://doi.org/10.1016/0165-3806(89)90042-4

Fishell, G., van der Kooy, D., 1987. Pattern formation in the striatum: developmental changes in the distribution of striatonigral neurons. J. Neurosci. Off. J. Soc. Neurosci. 7, 1969–1978.

Flaherty, A.W., Graybiel, A.M., 1994. Input-output organization of the sensorimotor striatum in the squirrel monkey. J. Neurosci. Off. J. Soc. Neurosci. 14, 599–610.

Freeze, B.S., Kravitz, A.V., Hammack, N., Berke, J.D., Kreitzer, A.C., 2013. Control of Basal Ganglia Output by Direct and Indirect Pathway Projection Neurons. J. Neurosci. 33, 18531–18539. https://doi.org/10.1523/JNEUROSCI.1278-13.2013

Friedman, A., Homma, D., Gibb, L.G., Amemori, K., Rubin, S.J., Hood, A.S., Riad, M.H., Graybiel, A.M., 2015. A Corticostriatal Path Targeting Striosomes Controls Decision-Making under Conflict. Cell 161, 1320–1333. https://doi.org/10.1016/j.cell.2015.04.049

Garel, S., Marín, F., Grosschedl, R., Charnay, P., 1999. Ebf1 controls early cell differentiation in the embryonic striatum. Dev. Camb. Engl. 126, 5285–5294.

Gauthier, L.R., Charrin, B.C., Borrell-Pagès, M., Dompierre, J.P., Rangone, H., Cordelières, F.P., De Mey, J., MacDonald, M.E., Leßmann, V., Humbert, S., Saudou, F., 2004. Huntingtin Controls Neurotrophic Support and Survival of Neurons by Enhancing

BDNF Vesicular Transport along Microtubules. Cell 118, 127–138. https://doi.org/10.1016/j.cell.2004.06.018

Gerfen, C., 1989. The neostriatal mosaic: striatal patch-matrix organization is related to cortical lamination. Science 246, 385–388. https://doi.org/10.1126/science.2799392

Gerfen, C.R., 1984. The neostriatal mosaic: compartmentalization of corticostriatal input and striatonigral output systems. Nature 311, 461–464. https://doi.org/10.1038/311461a0

Gerfen, C.R., Baimbridge, K.G., Miller, J.J., 1985. The neostriatal mosaic: compartmental distribution of calcium-binding protein and parvalbumin in the basal ganglia of the rat and monkey. Proc. Natl. Acad. Sci. 82, 8780–8784. https://doi.org/10.1073/pnas.82.24.8780

Graybiel, A.M., 1984. Correspondence between the Dopamine islands and striosomes of the mammalian striatum. Neuroscience 13, 1157–1187. https://doi.org/10.1016/0306-4522(84)90293-8

Graybiel, A.M., Ragsdale, C.W., 1978. Histochemically distinct compartments in the striatum of human, monkeys, and cat demonstrated by acetylthiocholinesterase staining. Proc. Natl. Acad. Sci. 75, 5723–5726. https://doi.org/10.1073/pnas.75.11.5723

Hagimoto, K., Takami, S., Murakami, F., Tanabe, Y., 2017. Distinct migratory behaviors of striosome and matrix cells underlying the mosaic formation in the developing striatum: Mosaic formation In the developing striatum. J. Comp. Neurol. 525, 794–817. https://doi.org/10.1002/cne.24096

Halliday, A.L., Cepko, C.L., 1992. Generation and migration of cells in the developing striatum. Neuron 9, 15–26. https://doi.org/10.1016/0896-6273(92)90216-Z

Hamasaki, T., Goto, S., Nishikawa, S., Ushio, Y., 2003. Neuronal cell migration for the developmental formation of the mammalian striatum. Brain Res. Rev. 41, 1–12. https://doi.org/10.1016/S0165-0173(02)00216-3

Harrington, D.L., Rubinov, M., Durgerian, S., Mourany, L., Reece, C., Koenig, K., Bullmore, E., Long, J.D., Paulsen, J.S., for the PREDICT-HD investigators of the Huntington Study Group, Rao, S.M., 2015. Network topology and functional connectivity disturbances precede the onset of Huntington's disease. Brain 138, 2332–2346. https://doi.org/10.1093/brain/awv145

Humbert, S., 2010. Is Huntington disease a developmental disorder? EMBO Rep. 11, 899–899. https://doi.org/10.1038/embor.2010.182

Jain, M., Armstrong, R.J.E., Barker, R.A., Rosser, A.E., 2001. Cellular and molecular aspects of striatal development. Brain Res. Bull. 55, 533–540. https://doi.org/10.1016/S0361-9230(01)00555-X

Jimenez-Castellanos, J., Graybiel, A.M., 1987. Subdivisions of the dopamine-containing A8-A9-A10 complex identified by their differential mesostriatal innervation of striosomes and extrastriosomal matrix. Neuroscience 23, 223–242. https://doi.org/10.1016/0306-4522(87)90285-5

Julien, C.L., Thompson, J.C., Wild, S., Yardumian, P., Snowden, J.S., Turner, G., Craufurd, D., 2007. Psychiatric disorders in preclinical Huntington's disease. J. Neurol. Neurosurg. Amp Psychiatry 78, 939–943. https://doi.org/10.1136/jnnp.2006.103309

Kawaguchi, Y., 1993. Physiological, morphological, and histochemical characterization of three classes of interneurons in rat neostriatum. J. Neurosci. Off. J. Soc. Neurosci. 13, 4908–4923.

Kelly, S.M., Raudales, R., He, M., Lee, J.H., Kim, Y., Gibb, L.G., Wu, P., Matho, K., Osten, P., Graybiel, A.M., Huang, Z.J., 2018. Radial Glial Lineage Progression and Differential Intermediate Progenitor Amplification Underlie Striatal Compartments and Circuit Organization. Neuron 99, 345-361.e4. https://doi.org/10.1016/j.neuron.2018.06.021

Kerschbamer, E., Biagioli, M., 2016. Huntington's Disease as Neurodevelopmental Disorder: Altered Chromatin Regulation, Coding, and Non-Coding RNA Transcription. Front. Neurosci. 9. https://doi.org/10.3389/fnins.2015.00509

Kincaid, A.E., Wilson, C.J., 1996. Corticostriatal innervation of the patch and matrix in the rat neostriatum. J. Comp. Neurol. 374, 578–592. https://doi.org/10.1002/(SICI)1096-9861(19961028)374:4<578::AID-CNE7>3.0.CO;2-Z

Kozorovitskiy, Y., Saunders, A., Johnson, C.A., Lowell, B.B., Sabatini, B.L., 2012. Recurrent network activity drives striatal synaptogenesis. Nature 485, 646–650. https://doi.org/10.1038/nature11052

Krajeski, R.N., Macey-Dare, A., Heusden, F., Ebrahimjee, F., Ellender, T.J., 2019. Dynamic postnatal development of the cellular and circuit properties of striatal D1 and D2 spiny projection neurons. J. Physiol. 597, 5265–5293. https://doi.org/10.1113/JP278416

Kravitz, A.V., Freeze, B.S., Parker, P.R.L., Kay, K., Thwin, M.T., Deisseroth, K., Kreitzer, A.C., 2010. Regulation of parkinsonian motor behaviours by optogenetic control of basal ganglia circuitry. Nature 466, 622–626. https://doi.org/10.1038/nature09159

Kress, G.J., Yamawaki, N., Wokosin, D.L., Wickersham, I.R., Shepherd, G.M.G., Surmeier, D.J., 2013. Convergent cortical innervation of striatal projection neurons. Nat. Neurosci. 16, 665–667. https://doi.org/10.1038/nn.3397

Lahiri, A.K., Bevan, M.D., 2020. Dopaminergic Transmission Rapidly and Persistently Enhances Excitability of D1 Receptor-Expressing Striatal Projection Neurons. Neuron 106, 277-290.e6. https://doi.org/10.1016/j.neuron.2020.01.028

Landwehrmeyer, G.B., McNeil, S.M., Dure, L.S., Ge, P., Aizawa, H., Huang, Q., Ambrose, C.M., Duyao, M.P., Bird, E.D., Bonilla, E., 1995. Huntington's disease gene: regional and cellular expression in brain of normal and affected individuals. Ann. Neurol. 37, 218–230. https://doi.org/10.1002/ana.410370213

Lee, J.K., Mathews, K., Schlaggar, B., Perlmutter, J., Paulsen, J.S., Epping, E., Burmeister, L., Nopoulos, P., 2012. Measures of growth in children at risk for Huntington disease. Neurology 79, 668–674. https://doi.org/10.1212/WNL.0b013e3182648b65

Lieberman, O.J., McGuirt, A.F., Mosharov, E.V., Pigulevskiy, I., Hobson, B.D., Choi, S., Frier, M.D., Santini, E., Borgkvist, A., Sulzer, D., 2018. Dopamine Triggers the Maturation of Striatal Spiny Projection Neuron Excitability during a Critical Period. Neuron 99, 540-554.e4. https://doi.org/10.1016/j.neuron.2018.06.044

Liot, G., Zala, D., Pla, P., Mottet, G., Piel, M., Saudou, F., 2013. Mutant Huntingtin Alters Retrograde Transport of TrkB Receptors in Striatal Dendrites. J. Neurosci. 33, 6298–6309. https://doi.org/10.1523/JNEUROSCI.2033-12.2013

Lobo, M.K., Karsten, S.L., Gray, M., Geschwind, D.H., Yang, X.W., 2006. FACS-array profiling of striatal projection neuron subtypes in juvenile and adult mouse brains. Nat. Neurosci. 9, 443–452. https://doi.org/10.1038/nn1654

Lobo, M.K., Yeh, C., Yang, X.W., 2008. Pivotal role of early B-cell factor 1 in development of striatonigral medium spiny neurons in the matrix compartment. J. Neurosci. Res. 86, 2134–2146. https://doi.org/10.1002/jnr.21666

Lopes, C., Aubert, S., Bourgois-Rocha, F., Barnat, M., Rego, A.C., Déglon, N., Perrier, A.L., Humbert, S., 2016. Dominant-Negative Effects of Adult-Onset Huntingtin Mutations Alter the Division of Human Embryonic Stem Cells-Derived Neural Cells. PLOS ONE 11, e0148680. https://doi.org/10.1371/journal.pone.0148680

Lu, K.-M., Evans, S.M., Hirano, S., Liu, F.-C., 2014. Dual role for Islet-1 in promoting striatonigral and repressing striatopallidal genetic programs to specify striatonigral cell identity. Proc. Natl. Acad. Sci. 111, E168–E177. https://doi.org/10.1073/pnas.1319138111

Marin, O., Anderson, S.A., Rubenstein, J.L., 2000. Origin and molecular specification of striatal interneurons. J. Neurosci. Off. J. Soc. Neurosci. 20, 6063–6076.

Marques Sousa, C., Humbert, S., 2013. Huntingtin: Here, There, Everywhere! J. Huntingt. Dis. 2, 395–403. https://doi.org/10.3233/JHD-130082

Martín-Ibáñez, R., Crespo, E., Esgleas, M., Urban, N., Wang, B., Waclaw, R., Georgopoulos, K., Martínez, S., Campbell, K., Vicario-Abejón, C., Alberch, J., Chan, S., Kastner, P., Rubenstein, J.L., Canals, J.M., 2012. *Helios* Transcription Factor Expression Depends on *Gsx2* and *Dlx1&2* Function in Developing Striatal Matrix Neurons. Stem Cells Dev. 21, 2239–2251. https://doi.org/10.1089/scd.2011.0607

Mason, H.A., Rakowiecki, S.M., Raftopoulou, M., Nery, S., Huang, Y., Gridley, T., Fishell, G., 2005. Notch signaling coordinates the patterning of striatal compartments. Dev. Camb. Engl. 132, 4247–4258. https://doi.org/10.1242/dev.02008

Mathkar, P.P., Suresh, D., Dunn, J., Tom, C.M., Mattis, V.B., 2019. Characterization of Neurodevelopmental Abnormalities in iPSC-Derived Striatal Cultures from Patients with Huntington's Disease. J. Huntingt. Dis. 8, 257–269. https://doi.org/10.3233/JHD-180333

McColgan, P., Tabrizi, S.J., 2018. Huntington's disease: a clinical review. Eur. J. Neurol. 25, 24–34. https://doi.org/10.1111/ene.13413

McGregor, M.M., McKinsey, G.L., Girasole, A.E., Bair-Marshall, C.J., Rubenstein, J.L.R., Nelson, A.B., 2019. Functionally Distinct Connectivity of Developmentally Targeted Striosome Neurons. Cell Rep. 29, 1419-1428.e5. https://doi.org/10.1016/j.celrep.2019.09.076

McKinstry, S.U., Karadeniz, Y.B., Worthington, A.K., Hayrapetyan, V.Y., Ozlu, M.I., Serafin-Molina, K., Risher, W.C., Ustunkaya, T., Dragatsis, I., Zeitlin, S., Yin, H.H., Eroglu, C., 2014. Huntingtin Is Required for Normal Excitatory Synapse Development in Cortical and Striatal Circuits. J. Neurosci. 34, 9455–9472. https://doi.org/10.1523/JNEUROSCI.4699-13.2014

Mehler, M.F., Gokhan, S., 2001. Developmental mechanisms in the pathogenesis of neurodegenerative diseases. Prog. Neurobiol. 63, 337–363. https://doi.org/10.1016/S0301-0082(00)00052-6

Mehler, M.F., Petronglo, J.R., Arteaga-Bracho, E.E., Gulinello, M.E., Winchester, M.L., Pichamoorthy, N., Young, S.K., DeJesus, C.D., Ishtiaq, H., Gokhan, S., Molero, A.E., 2019. Loss-of-Huntingtin in Medial and Lateral Ganglionic Lineages Differentially Disrupts Regional Interneuron and Projection Neuron Subtypes and Promotes Huntington's Disease-Associated Behavioral, Cellular, and Pathological Hallmarks. J. Neurosci. 39, 1892–1909. https://doi.org/10.1523/JNEUROSCI.2443-18.2018

Merchan-Sala, P., Nardini, D., Waclaw, R.R., Campbell, K., 2017. Selective neuronal expression of the SoxE factor, Sox8, in direct pathway striatal projection neurons of the developing mouse brain: MERCHAN-SALA et al. J. Comp. Neurol. 525, 2805–2819. https://doi.org/10.1002/cne.24232

Molero, A.E., Arteaga-Bracho, E.E., Chen, C.H., Gulinello, M., Winchester, M.L., Pichamoorthy, N., Gokhan, S., Khodakhah, K., Mehler, M.F., 2016. Selective expression of mutant huntingtin during development recapitulates characteristic features of Huntington's disease. Proc. Natl. Acad. Sci. 113, 5736–5741. https://doi.org/10.1073/pnas.1603871113

Molero, A.E., Gokhan, S., Gonzalez, S., Feig, J.L., Alexandre, L.C., Mehler, M.F., 2009. Impairment of developmental stem cell-mediated striatal neurogenesis and pluripotency genes in a knock-in model of Huntington's disease. Proc. Natl. Acad. Sci. 106, 21900–21905. https://doi.org/10.1073/pnas.0912171106

Muñoz-Manchado, A.B., Bengtsson Gonzales, C., Zeisel, A., Munguba, H., Bekkouche, B., Skene, N.G., Lönnerberg, P., Ryge, J., Harris, K.D., Linnarsson, S., Hjerling-Leffler, J., 2018. Diversity of Interneurons in the Dorsal Striatum Revealed by Single-Cell RNA Sequencing and PatchSeq. Cell Rep. 24, 2179-2190.e7. https://doi.org/10.1016/j.celrep.2018.07.053

Nakamura, K., Hioki, H., Fujiyama, F., Kaneko, T., 2005. Postnatal changes of vesicular glutamate transporter (VGluT)1 and VGluT2 immunoreactivities and their colocalization in the mouse forebrain. J. Comp. Neurol. 492, 263–288. https://doi.org/10.1002/cne.20705

Nasir, J., Floresco, S.B., O'Kusky, J.R., Diewert, V.M., Richman, J.M., Zeisler, J., Borowski, A., Marth, J.D., Phillips, A.G., Hayden, M.R., 1995. Targeted disruption of the Huntington's disease gene results in embryonic lethality and behavioral and morphological changes in heterozygotes. Cell 81, 811–823. https://doi.org/10.1016/0092-8674(95)90542-1

Newman, H., Liu, F.-C., Graybiel, A.M., 2015. Dynamic ordering of early generated striatal cells destined to form the striosomal compartment of the striatum: Compartment formation in the striatum. J. Comp. Neurol. 523, 943–962. https://doi.org/10.1002/cne.23725

Nóbrega-Pereira, S., Gelman, D., Bartolini, G., Pla, R., Pierani, A., Marin, O., 2010. Origin and Molecular Specification of Globus Pallidus Neurons. J. Neurosci. 30, 2824–2834. https://doi.org/10.1523/JNEUROSCI.4023-09.2010

Nóbrega-Pereira, S., Kessaris, N., Du, T., Kimura, S., Anderson, S.A., Marín, O., 2008. Postmitotic Nkx2-1 Controls the Migration of Telencephalic Interneurons by Direct Repression of Guidance Receptors. Neuron 59, 733–745. https://doi.org/10.1016/j.neuron.2008.07.024

Paulsen, J.S., Nopoulos, P.C., Aylward, E., Ross, C.A., Johnson, H., Magnotta, V.A., Juhl, A., Pierson, R.K., Mills, J., Langbehn, D., Nance, M., 2010. Striatal and white matter predictors of estimated diagnosis for Huntington disease. Brain Res. Bull. 82, 201–207. https://doi.org/10.1016/j.brainresbull.2010.04.003

Peixoto, R.T., Wang, W., Croney, D.M., Kozorovitskiy, Y., Sabatini, B.L., 2016. Early hyperactivity and precocious maturation of corticostriatal circuits in Shank3B−/− mice. Nat. Neurosci. 19, 716–724. https://doi.org/10.1038/nn.4260

Pert, C.B., Kuhar, M.J., Snyder, S.H., 1976. Opiate receptor: autoradiographic localization in rat brain. Proc. Natl. Acad. Sci. 73, 3729–3733. https://doi.org/10.1073/pnas.73.10.3729

Petralia, R.S., Esteban, J.A., Wang, Y. –X., Partridge, J.G., Zhao, H. –M., Wenthold, R.J., Malinow, R., 1999. Selective acquisition of AMPA receptors over postnatal development suggests a molecular basis for silent synapses. Nat. Neurosci. 2, 31–36. https://doi.org/10.1038/4532

Pilz, G.-A., Shitamukai, A., Reillo, I., Pacary, E., Schwausch, J., Stahl, R., Ninkovic, J., Snippert, H.J., Clevers, H., Godinho, L., Guillemot, F., Borrell, V., Matsuzaki, F., Götz, M., 2013. Amplification of progenitors in the mammalian telencephalon includes a new radial glial cell type. Nat. Commun. 4, 2125. https://doi.org/10.1038/ncomms3125

Planert, H., Berger, T.K., Silberberg, G., 2013. Membrane Properties of Striatal Direct and Indirect Pathway Neurons in Mouse and Rat Slices and Their Modulation by Dopamine. PLoS ONE 8, e57054. https://doi.org/10.1371/journal.pone.0057054

Prager, E.M., Plotkin, J.L., 2019. Compartmental function and modulation of the striatum. J. Neurosci. Res. jnr.24522. https://doi.org/10.1002/jnr.24522

Reiner, A., Anderson, K.D., 1990. The patterns of neurotransmitter and neuropeptide co-occurrence among striatal projection neurons: conclusions based on recent findings. Brain Res. Rev. 15, 251–265. https://doi.org/10.1016/0165-0173(90)90003-7

Reiner, A., Del Mar, N., Meade, C.A., Yang, H., Dragatsis, I., Zeitlin, S., Goldowitz, D., 2001. Neurons lacking huntingtin differentially colonize brain and survive in chimeric mice. J. Neurosci. Off. J. Soc. Neurosci. 21, 7608–7619.

Reiner, A., Deng, Y.-P., 2018. Disrupted striatal neuron inputs and outputs in Huntington's disease. CNS Neurosci. Ther. 24, 250–280. https://doi.org/10.1111/cns.12844

Rigamonti, D., Sipione, S., Goffredo, D., Zuccato, C., Fossale, E., Cattaneo, E., 2001. Huntingtin's Neuroprotective Activity Occurs via Inhibition of Procaspase-9 Processing. J. Biol. Chem. 276, 14545–14548. https://doi.org/10.1074/jbc.C100044200

Ring, K.L., An, M.C., Zhang, N., O'Brien, R.N., Ramos, E.M., Gao, F., Atwood, R., Bailus, B.J., Melov, S., Mooney, S.D., Coppola, G., Ellerby, L.M., 2015. Genomic Analysis Reveals Disruption of Striatal Neuronal Development and Therapeutic Targets in Human Huntington's Disease Neural Stem Cells. Stem Cell Rep. 5, 1023–1038. https://doi.org/10.1016/j.stemcr.2015.11.005

Ross, C.A., Tabrizi, S.J., 2011. Huntington's disease: from molecular pathogenesis to clinical treatment. Lancet Neurol. 10, 83–98. https://doi.org/10.1016/S1474-4422(10)70245-3

Ruzo, A., Croft, G.F., Metzger, J.J., Galgoczi, S., Gerber, L.J., Pellegrini, C., Wang, H., Fenner, M., Tse, S., Marks, A., Nchako, C., Brivanlou, A.H., 2018. Chromosomal instability during neurogenesis in Huntington's disease. Development 145, dev156844. https://doi.org/10.1242/dev.156844

Saudou, F., Humbert, S., 2016. The Biology of Huntingtin. Neuron 89, 910–926. https://doi.org/10.1016/j.neuron.2016.02.003

Sharpe, N.A., Tepper, J.M., 1998. Postnatal development of excitatory synaptic input to the rat neostriatum: An electron microscopic study. Neuroscience 84, 1163–1175. https://doi.org/10.1016/S0306-4522(97)00583-6

Shirasaki, D.I., Greiner, E.R., Al-Ramahi, I., Gray, M., Boontheung, P., Geschwind, D.H., Botas, J., Coppola, G., Horvath, S., Loo, J.A., Yang, X.W., 2012. Network Organization of the Huntingtin Proteomic Interactome in Mammalian Brain. Neuron 75, 41–57. https://doi.org/10.1016/j.neuron.2012.05.024

Silberberg, G., Bolam, J.P., 2015. Local and afferent synaptic pathways in the striatal microcircuitry. Curr. Opin. Neurobiol. 33, 182–187. https://doi.org/10.1016/j.conb.2015.05.002

Sohur, U.S., Padmanabhan, H.K., Kotchetkov, I.S., Menezes, J.R.L., Macklis, J.D., 2014. Anatomic and Molecular Development of Corticostriatal Projection Neurons in Mice. Cereb. Cortex 24, 293–303. https://doi.org/10.1093/cercor/bhs342

Solomon, A.C., Stout, J.C., Johnson, S.A., Langbehn, D.R., Aylward, E.H., Brandt, J., Ross, C.A., Beglinger, L., Hayden, M.R., Kieburtz, K., Kayson, E., Julian-Baros, E., Duff, K., Guttman, M., Nance, M., Oakes, D., Shoulson, I., Penziner, E., Paulsen, J.S., 2007. Verbal episodic memory declines prior to diagnosis in Huntington's disease. Neuropsychologia 45, 1767–1776. https://doi.org/10.1016/j.neuropsychologia.2006.12.015

Song, D.D., Harlan, R.E., 1994. Genesis and migration patterns of neurons forming the patch and matrix compartments of the rat striatum. Dev. Brain Res. 83, 233–245. https://doi.org/10.1016/0165-3806(94)00144-8

Sousa, V.H., Fishell, G., 2010. Sonic hedgehog functions through dynamic changes in temporal competence in the developing forebrain. Curr. Opin. Genet. Dev. 20, 391–399. https://doi.org/10.1016/j.gde.2010.04.008

Spitzer, N.C., 2006. Electrical activity in early neuronal development. Nature 444, 707–712. https://doi.org/10.1038/nature05300

Tepper, J.M., Koós, T., Ibanez-Sandoval, O., Tecuapetla, F., Faust, T.W., Assous, M., 2018. Heterogeneity and Diversity of Striatal GABAergic Interneurons: Update 2018. Front. Neuroanat. 12, 91. https://doi.org/10.3389/fnana.2018.00091

Tepper, J.M., Sharpe, N.A., Koós, T.Z., Trent, F., 1998. Postnatal Development of the Rat Neostriatum: Electrophysiological, Light- and Electron-Microscopic Studies. Dev. Neurosci. 20, 125–145. https://doi.org/10.1159/000017308

Tepper, J.M., Trent, F., 1993. In vivo studies of the postnatal development of rat neostriatal neurons. Prog. Brain Res. 99, 35–50. https://doi.org/10.1016/s0079-6123(08)61337-0

Tereshchenko, A.V., Schultz, J.L., Bruss, J.E., Magnotta, V.A., Epping, E.A., Nopoulos, P.C., 2020. Abnormal development of cerebellar-striatal circuitry in Huntington disease. Neurology. https://doi.org/10.1212/WNL.0000000000009364

The HD iPSC Consortium, 2017. Developmental alterations in Huntington's disease neural cells and pharmacological rescue in cells and mice. Nat. Neurosci. 20, 648–660. https://doi.org/10.1038/nn.4532

The Huntington's Disease collaborative research group, M., 1993. A novel gene containing a trinucleotide repeat that is expanded and unstable on Huntington's disease chromosomes. Cell 72, 971–983. https://doi.org/10.1016/0092-8674(93)90585-E

Tinterri, A., Menardy, F., Diana, M.A., Lokmane, L., Keita, M., Coulpier, F., Lemoine, S., Mailhes, C., Mathieu, B., Merchan-Sala, P., Campbell, K., Gyory, I., Grosschedl, R., Popa, D., Garel, S., 2018. Active intermixing of indirect and direct neurons builds the striatal mosaic. Nat. Commun. 9, 4725. https://doi.org/10.1038/s41467-018-07171-4

Turrero García, M., Harwell, C.C., 2017. Radial glia in the ventral telencephalon. FEBS Lett. 591, 3942–3959. https://doi.org/10.1002/1873-3468.12829

van der Kooy, D., Fishell, G., 1987. Neuronal birthdate underlies the development of striatal compartments. Brain Res. 401, 155–161. https://doi.org/10.1016/0006-8993(87)91176-0

van der Plas, E., Langbehn, D.R., Conrad, A.L., Koscik, T.R., Tereshchenko, A., Epping, E.A., Magnotta, V.A., Nopoulos, P.C., 2019. Abnormal brain development in child and adolescent carriers of mutant huntingtin. Neurology 93, e1021–e1030. https://doi.org/10.1212/WNL.0000000000008066

Voorn, P., Kalsbeek, A., Jorritsma-Byham, B., Groenewegen, H.J., 1988. The pre- and postnatal development of the dopaminergic cell groups in the ventral mesencephalon and the dopaminergic innervation of the striatum of the rat. Neuroscience 25, 857–887. https://doi.org/10.1016/0306-4522(88)90041-3

Watabe-Uchida, M., Zhu, L., Ogawa, S.K., Vamanrao, A., Uchida, N., 2012. Whole-Brain Mapping of Direct Inputs to Midbrain Dopamine Neurons. Neuron 74, 858–873. https://doi.org/10.1016/j.neuron.2012.03.017

Wiatr, K., Szlachcic, W.J., Trzeciak, M., Figlerowicz, M., Figiel, M., 2018. Huntington Disease as a Neurodevelopmental Disorder and Early Signs of the Disease in Stem Cells. Mol. Neurobiol. 55, 3351–3371. https://doi.org/10.1007/s12035-017-0477-7

Wiegand, M., Möller, A.A., Lauer, C.J., Stolz, S., Schreiber, W., Dose, M., Krieg, J.C., 1991. Nocturnal sleep in Huntington's disease. J. Neurol. 238, 203–208. https://doi.org/10.1007/bf00314781

Wilson, C.J., Groves, P.M., 1980. Fine structure and synaptic connections of the common spiny neuron of the rat neostriatum: A study employing intracellular injection of horseradish peroxidase. J. Comp. Neurol. 194, 599–615. https://doi.org/10.1002/cne.901940308

Xu, Z., Liang, Q., Song, X., Zhang, Z., Lindtner, S., Li, Z., Wen, Y., Liu, G., Guo, T., Qi, D., Wang, M., Wang, C., Li, H., You, Y., Wang, X., Chen, B., Feng, H., Rubenstein, J.L., Yang, Z., 2018. SP8 and SP9 coordinately promote D2-type medium spiny neuron production by activating *Six3* expression. Development 145, dev165456. https://doi.org/10.1242/dev.165456

Yun, K., Fischman, S., Johnson, J., Hrabe de Angelis, M., Weinmaster, G., Rubenstein, J.L.R., 2002. Modulation of the notch signaling by Mash1 and Dlx1/2 regulates sequential specification and differentiation of progenitor cell types in the subcortical telencephalon. Dev. Camb. Engl. 129, 5029–5040.

Zeitlin, S., Liu, J.-P., Chapman, D.L., Papaioannou, V.E., Efstratiadis, A., 1995. Increased apoptosis and early embryonic lethality in mice nullizygous for the Huntington's disease gene homologue. Nat. Genet. 11, 155–163. https://doi.org/10.1038/ng1095-155

Zhang, Q., Zhang, Y., Wang, C., Xu, Z., Liang, Q., An, L., Li, J., Liu, Z., You, Y., He, M., Mao, Y., Chen, B., Xiong, Z.-Q., Rubenstein, J.L., Yang, Z., 2016. The Zinc Finger Transcription Factor Sp9 Is Required for the Development of Striatopallidal Projection Neurons. Cell Rep. 16, 1431–1444. https://doi.org/10.1016/j.celrep.2016.06.090

Zhang, Y., Leavitt, B.R., van Raamsdonk, J.M., Dragatsis, I., Goldowitz, D., MacDonald, M.E., Hayden, M.R., Friedlander, R.M., 2006. Huntingtin inhibits caspase-3 activation. EMBO J. 25, 5896–5906. https://doi.org/10.1038/sj.emboj.7601445

Zuccato, C., Ciammola, A., Rigamonti, D., Leavitt, B.R., Goffredo, D., Conti, L., MacDonald, M.E., Friedlander, R.M., Silani, V., Hayden, M.R., Timmusk, T., Sipione, S., Cattaneo, E., 2001. Loss of huntingtin-mediated BDNF gene transcription in Huntington's disease. Science 293, 493–498. https://doi.org/10.1126/science.1059581