

1 **TITLE: Premature MeCP2 Expression Disturbs the Subtype Specification of**
2 **Midbrain Dopamine Neurons.**

3 Running title: MeCP2 and dopamine subtype specification.

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1 **Abstract**

2 Midbrain dopamine (DA) neurons are associated with locomotor and psychiatric
3 disorders. DA subtype is specified in ancestral neural precursor cells (NPCs) and
4 maintained throughout neuronal differentiation. Here we show that endogenous
5 expression of MeCP2 coincides with DA subtype specification in mouse
6 mesencephalon, and premature expression of MeCP2 prevents in vitro cultured NPCs
7 from acquiring DA subtype through interfering NURR1 transactivation of DA
8 phenotype genes. By contrast, MeCP2 overexpression does not disturb DA subtype in
9 DA neurons. By analyzing the dynamic change of DNA methylation along DA
10 neuronal differentiation at the promoter of DA phenotype gene tyrosine hydroxylase
11 (*Th*), we show that *Th* expression is determined by TET1-mediated de-methylation of
12 NURR1 binding sites within *Th* promoter. Chromatin immunoprecipitation assays
13 demonstrate that MeCP2 dominates the DNA binding of the corresponding sites
14 thereby blocking TET1 function in DA NPCs, whereas TET1-mediated
15 de-methylation prevents excessive MeCP2 binding in DA neurons. The significance
16 of temporal DNA methylation status is further confirmed by targeted
17 methylation/demethylation experiments showing that targeted de-methylation in DA
18 NPCs protects DA subtype specification from MeCP2 overexpression, whereas
19 targeted methylation disturbs subtype maintenance in MeCP2-overexpressed DA
20 neurons. These findings suggest the appropriate timing of MeCP2 expression as a
21 novel determining factor for guiding NPCs into DA lineage.

1 **Introduction**

2 Neurogenesis is characterized by generic neuronal differentiation and
3 neurotransmitter subtype specification of neural precursor cells (NPCs), two
4 developmental programs contributing to the molecular, cellular and functional
5 specificity of different neurons in CNS. These two programs are under precise
6 spatio-temporal control of a variety of extrinsic cues and intrinsic transcription factors
7 and epigenetic modifications. Some transcription factors contribute to each program
8 independently, whereas others are involved in both. For instance, in the neurogenesis
9 of midbrain dopamine (DA) neurons, mutation of nuclear orphan receptor gene *Nurr1*
10 impairs the DA subtype specification but not the general neuronal differentiation of
11 DA NPCs (Zetterström, 1997), whereas lack of proneural gene *Ngn2* results in failed
12 acquisition of DA subtype and general neuronal differentiation (Andersson, 2006).
13 Understanding how neuronal subtype specification and general neuronal
14 differentiation are coordinated to reach a complete neurogenesis provides the
15 fundamental basis for the development of stem cell therapy which aims at generating
16 specific neuronal cells with full functionality from embryonic stem cells and induced
17 pluripotent stem cells.

18

19 The subtype specification of midbrain DA neurons is transcriptionally characterized
20 by constitutive expression of DA phenotype genes such as *Th* encoding the DA
21 synthesis rate limiting enzyme tyrosine hydroxylase and *Aadc* encoding aromatic
22 L-amino acid decarboxylase, both of which are responsible for the conversion of

1 L-tyrosine into DA. *Th* is also one of the earliest expressed DA phenotype genes that
2 is maintained throughout DA neuron lifespan. The subtype specification of midbrain
3 DA neurons marks the fate commitment of NPCs into DA lineage in embryonic
4 brains, and the maintenance of DA phenotype is essential for mature DA neuronal
5 functions, loss of which in adult midbrains is associated with movement and
6 emotional disorders such as Parkinson's disease and schizophrenia (Arenas et al.,
7 2015; Goridis and Rohrer, 2002; Hynes and Rosenthal, 1999). Nuclear receptor
8 related 1 protein (NURR1) is a master regulator for the subtype specification of
9 midbrain DA neurons, expression of which in mouse is initiated in DA NPCs residing
10 in the ventral mesencephalon at embryonic day E10.5 (Ang, 2006). Continuous
11 activation of *Nurr1* is implicated in the subtype specification as well as the
12 maintenance of midbrain DA neurons. Genetic ablation of *Nurr1* in transgenic mice
13 resulted in absence of DA phenotype (Saucedo-Cardenas et al., 1998; Zetterström,
14 1997). Conditional ablation of *Nurr1* caused loss of DA phenotype in maturing DA
15 neurons (Kadkhodaei et al., 2009). By contrast, ectopic expression of *Nurr1* is able to
16 force the expression of these markers in non-DA cells(Kim et al., 2003a; Shim et al.,
17 2007; Wagner et al., 1999). A large number of studies including ours have
18 demonstrated that NURR1 facilitates DA subtype specification through direct
19 transactivation of the promoter activity of DA phenotype genes including *Th* and
20 *Aadc* (He et al., 2011, 2015; Kim et al., 2003b; Park et al., 2008; Yi et al., 2014).
21 Based on this well-elucidated mechanism, various transcription factors and epigenetic
22 factors have been identified to cooperate with NURR1 in DA subtype specification

1 (van Heesbeen et al., 2013), including DNA hydroxymethylase ten-eleven
2 translocation 1 (TET1) and TET1-induced DNA de-methylation (He et al., 2015).
3 However, the implication of DNA methylation and DNA methylation-related
4 molecules in NURR1-mediated DA subtype specification remains to be elucidated.

5

6 X-linked gene *Mecp2*-encoded Methyl-CpG binding protein 2 (MeCP2) recognizes
7 and binds to methylated and unmethylated CG dinucleotide to modulate chromatin
8 structure and gene expression. Genetic loss or gain of *Mecp2* is associated with
9 neurological and developmental disorders Rett syndrome and *Mecp2* duplication
10 syndrome, respectively. In developing brain, MeCP2 expression highly correlates
11 with neurogenesis and is involved in general neuronal differentiation and synapse
12 plasticity (Cassel et al., 2004; Chen, 2003, 2003; Jung et al., 2003; Matarazzo et al.,
13 2004; Tate et al., 1996; Tsujimura et al., 2009). Evidence exist that have suggested the
14 association of MeCP2 with DA-related disorders. For instance, deficit of MeCP2
15 expression in the brain is associated with DA metabolites abnormality in patients and
16 animal models of Rett syndrome (Gantz et al., 2011; Ide et al., 2005; Kao et al., 2015;
17 Panayotis et al., 2011b, 2011a; Samaco et al., 2009; Zhao et al., 2013). Underlying
18 mechanisms include autonomous deficits of key DA synthesizing enzymes including
19 TH in DA neurons of substantia nigra (SN) and striatum, and non-autonomous effects
20 derived from serotonin neurons. *Mecp2* duplication syndrome, a neurodevelopmental
21 disorder shares many similar behavioral and molecular deficits with Rett syndrome,
22 including abnormal DA levels and motor function (Na et al., 2012; Peters et al., 2013).

1 Although the roles of MeCP2 for general neuronal maturation and functions have
2 been widely revealed, little is known about the contribution of MeCP2 to the subtype
3 specification and maintenance of DA neurons.

4

5 We previously have shown that the dissociation of MeCP2 from promoters of DA
6 phenotype genes is required to facilitate NPCs into DA lineage (He et al., 2011). This
7 finding was extended in this study by inducing MeCP2 expression before or after DA
8 subtype specification to elucidate consequences of abnormal timing and dose of
9 MeCP2 expression to the subtype specification and maintenance of midbrain DA
10 neurons.

1 **Results**

2 **NURR1 precedes MeCP2 expression in DA neurogenesis.**

3 The initiation of NURR1 expression in the ventricular zone of mouse ventral
4 mesencephalon at E10.5 marks the identity of undifferentiated DA NPCs and start of
5 DA subtype specification, followed by ventral-lateral migration of these cells and
6 immediate expression of DA phenotype gene *Th* in the intermediate and mantle zones
7 at E12.5. To understand the association of MeCP2 and development of DA neuronal
8 subtype, the expression pattern of NURR1 and MeCP2 was examined by
9 immunofluorescence analysis in ventral regions of E10.5, E12.5 and postnatal day 28
10 (P28) mouse midbrains, where reside DA NPCs before subtype specification,
11 immature DA neurons after subtype specification and mature DA neurons after
12 differentiation, respectively (Ang, 2006). At E10.5, NURR1 was already expressed in
13 the ventricular zone but not co-expressed with TH, confirming that these cells were
14 DA NPCs not yet undergoing DA subtype specification. Notably, these NURR1+ DA
15 NPCs were negative for MeCP2 (Fig. 1A). At E12.5, however, MeCP2 started to get
16 expressed by NURR1+ cells around the midline of intermediate zone and in the
17 mantle zone, in which TH was also expressed. These results demonstrated a
18 sequential expression of NURR1 and MeCP2 across the period of DA subtype
19 specification, and suggested a coincidence of MeCP2 expression and onset of DA
20 subtype specification. Consistent with this, MeCP2 was expressed in all the
21 TH+Nurr1+ mature DA neurons in ventral tegmental area (VTA) and SN at P28.
22 These *in situ* expression analyses demonstrated a concurrent onset of MeCP2

1 expression and DA subtype specification, both of which were preceded by NURR1
2 expression for about one embryonic day in mouse mesencephalon (depicted in Fig.
3 1B).

4

5 In our lab, mitotic DA NPCs extracted from mouse ventral mesencephalon at E10.5
6 can be expanded and induced to differentiate into midbrain DA neurons within 6 days
7 of neuronal differentiation *in vitro* (DIV), serving as a well-defined cell model to
8 study the mechanisms underlying subtype specification and neuronal differentiation
9 of midbrain DA neurons (He et al., 2011, 2015). This model was recruited to confirm
10 the sequential expression of NURR1 and MeCP2 observed in embryonic development.

11 At DIV0, NURR1+TH- DA NPCs were not expressing MeCP2, whereas
12 NURR1+TH+ DA neurons at DIV3 and DIV6 were expressing MeCP2 (Fig. 1C).

13 Therefore, the DA neuron differentiation cell culture well recapitulated the midbrain
14 DA neuron development *in vivo* (depicted in Fig. 1D). These results collectively
15 demonstrate a dynamic appearance of endogenous MeCP2 throughout the neuronal
16 differentiation of DA NPCs towards DA neurons. In particular, in DA NPCs, MeCP2
17 was not expressed until DA subtype was specified, suggesting a hypothetical
18 necessity of restricting MeCP2 expression in DA NPCs for the proper specification of
19 DA subtype.

20

21 **Premature MeCP2 expression abolishes DA subtype specification.**

22 To test this hypothesis, a lentivirus carrying sequence encoding a

1 tetracycline-inducible MeCP2 was transduced into cultured mitotic NPCs before DA
2 neuronal differentiation. Time- and dose-specific MeCP2 overexpression was induced
3 by addition of 0.1-2 μ M doxycycline (Dx) at first three days of DIV, when either
4 endogenous MeCP2 or DA phenotype marker TH was not expressed yet. In parallel,
5 same Dx treatment was applied at last three days of DIV to induce an overdose of
6 MeCP2 after DA subtype specification. At DIV6, the yield of TH+ cells representing
7 differentiated DA neurons was measured (Fig. 2A). We found that MeCP2
8 overexpression in early period of differentiation remarkably reduced the terminal
9 yield of TH+ cells (Fig. 2B). Interestingly, 0.1 μ M Dx resulted in comparable yield
10 reduction of TH+ cells as 2 μ M Dx, suggesting no additional influence from dosage
11 of ectopic MeCP2. By contrast, the yield of TH+ cells was not affected by MeCP2
12 overexpression in late period of differentiation. Molecular analysis demonstrated that
13 the mRNA levels of *Th* and *Aadc* were decreased only when MeCP2 was
14 overexpressed in early but not late period of differentiation (Fig. 2C), suggesting that
15 the subtype specification in DA NPCs was transcriptionally regulated by MeCP2.
16 Collectively, these results demonstrate differential consequences of MeCP2
17 overexpression to the subtype specification and maintenance of DA neurons.

18
19 Protein structure studies have identified two functional domains in MeCP2, namely
20 DNA binding domain (DBD) and transcriptional repressing domain (TRD). To further
21 dissect the domain functionality of MeCP2 in DA subtype specification, DA NPCs
22 were infected with lentiviruses carrying sequences encoding full-length MeCP2 or

1 R168X, a truncated mutation containing intact DBD but not TRD. A sequence
2 encoding ZsGreen1 fluorescent protein (GFP) was incorporated to label the infected
3 cells. We found that overexpression of MeCP2 from DIV0 significantly reduced the
4 yield of TH+ cells at DIV6, verifying the results observed from Dx-induced MeCP2
5 overexpression. However, overexpression of R168X did not alter the yield of TH+
6 cells (Fig. 2D), indicating that the TRD of MeCP2 is responsible for the disturbance
7 of DA subtype specification in DA NPCs. Notably, TH and GFP double positive cells
8 were found in cells infected by empty vector or R168X, but not in cells infected by
9 MeCP2 (Fig. 2E), indicating that MeCP2 disturbed DA subtype specification in a
10 cell-autonomous manner.

11

12 **MeCP2 impedes NURR1 transactivation of DA phenotype genes in DA NPCs.**

13 NURR1 overexpression is sufficient to induce expression of DA phenotype genes
14 especially *Th* even in non-DA lineage cells such as rodent embryonic cortical NPCs.
15 We recruited this system to gain a direct insight into the association of MeCP2 and
16 NURR1 in DA subtype specification. As the TH-inducing effect has been reported
17 much more effective in NPCs derived from rat than mouse (Lee et al., 2009; Park et
18 al., 2008), rat embryonic cortical NPCs were co-infected with lentivirus encoding
19 NURR1 and that encoding MeCP2 or R168X. About 50% of cells infected with
20 NURR1 and control viruses started to express TH within 3 days, confirming the
21 efficiency of NURR1-induced TH expression. MeCP2 overexpression greatly reduced
22 this population to about 2% (Fig. 3A-B). Co-labeling of TH and GFP showed that the

1 majority of cells overexpressing MeCP2 were negative for TH (Fig. 3C), consistently
2 indicating a cell-autonomous effect of MeCP2. Overexpression of R168X also did not
3 affect the yield of TH+ cells. Real-time PCR analysis demonstrated a transcriptional
4 repression of *Aadc* as *Th* by MeCP2 but not R168X, a result similar to the
5 overexpression outcome in DA NPCs (Fig. 3D). Given that NPCs from embryonic
6 cortices do not possess the majority of molecular machinery for DA neuron
7 development, it appears safe to conclude that ectopic MeCP2 targets
8 NURR1-mediated molecular machinery to inhibit DA phenotype gene expression.

9

10 A large number of studies including ours have reported that recruitment of NURR1
11 onto the promoters of DA phenotype genes as the molecular mechanism for the
12 initiation of their transcription. In particular, NURR1 transactivates *Th* gene
13 expression through binding to NURR1 binding motif namely NBRE on *Th* promoter.
14 Therefore, we performed a series of ChIP experiments to examine how MeCP2
15 interacts with NURR1 on the promoter of *Th* gene in both DA NPCs and DA neurons.
16 Within 1 kilo bp distance upstream to transcription starting site of mouse *Th* gene,
17 there are three NBREs (Fig. 3E). When overexpressed in DA NPCs, MeCP2
18 occupancy of all three NBREs was remarkably increased (Fig. 3F), whereas the
19 binding of NURR1 was reduced (Fig. 3G). Interestingly, the binding of R168X was
20 also increased, but it did not decrease the binding of NURR1. The best explanation of
21 this result is that the binding of NURR1 to NBRE sites might be interfered by the
22 TRD of MeCP2, rather than a competitive binding for NURR1 and MeCP2.

1

2 By contrast, when overexpressed in DA neurons, enrichment of NURR1 onto NBREs
3 was not altered by overexpression of either MeCP2 or R168X (Fig. 3I). Importantly,
4 the recruitment of MeCP2 onto NBREs was not increased by overexpression of
5 MeCP2 or R168X (Fig. 3H), raising the possibility that the *Th* gene in DA neurons
6 was not accessible to direct binding of MeCP2. Taken together, the data presented
7 here demonstrate differential impact of MeCP2 overexpression on NURR1-mediated
8 transactivation of DA phenotype genes in DA NPCs and DA neurons.

9

10 **MeCP2 competes TET1 to block DA subtype specification.**

11 We previously have revealed an essential role of TET1-mediated DNA
12 de-methylation for NURR1 to transactivate the expression of DA phenotype genes
13 (He et al., 2015). Therefore, we hypothesized that the DNA methylation status of DA
14 phenotype genes distinguished the DNA binding and function of MeCP2 in DA NPCs
15 and DA neurons. Consistent with the TET-assisted and bisulfite sequencing data in
16 our previous study, hydroxymethylated/methylated DNA immunoprecipitation
17 (hMeDIP/MeDIP) analyses confirmed that the 5mC level within 1 kilo bp of *Th*
18 promoter was decreased along DA neuronal differentiation, in concert with the
19 increase of 5hmC level (Fig. 4A). Accordingly, enrichment of TET1 on *Th* promoter,
20 especially on the NBREs, was significantly increased (Fig. 4B), indicating that TET1
21 was responsible for the 5mC oxidation of *Th* promoter along DA neuronal
22 differentiation. Interestingly, overexpression of MeCP2 in DA NPCs caused increased

1 level of 5mC and decreased level of 5hmC after differentiation, suggesting that the
2 natural alterations of these epigenetic marks along with differentiation were prevented
3 by premature MeCP2 expression (Fig. 4C). In addition, ChIP analysis demonstrated
4 that TET1 was much less recruited onto *Th* promoter by MeCP2 overexpression in
5 DA NPCs (Fig. 4D). These results suggested that MeCP2 overexpression in DA
6 NPCs abolished DNA de-methylation of DA phenotype genes through interfering
7 TET1 function.

8

9 To validate whether DNA methylation of *Th* promoter is necessary for MeCP2
10 binding in DA NPCs, vitamin C (VC) was added to MeCP2-overexpressed DA NPCs
11 for the purpose of a global DNA de-methylation. As previously reported (He et al.,
12 2015), VC significantly increased the yield of TH+ cells. As shown in Fig. 2D, in the
13 absence of VC, overexpression of MeCP2 but not R168X decreased the yield of TH+
14 cells. However, addition of VC completely reversed the impact of MeCP2
15 overexpression (Fig. 4E). Furthermore, VC remarkably decreased the enrichment of
16 MeCP2 on the NBREs of *Th* promoter in MeCP2-overexpressed DA NPCs (Fig. 4F).
17 These findings suggested direct associations between DNA de-methylation and *Th*
18 gene expression with MeCP2 binding in the process of DA subtype specification. To
19 further improve the specificity of DNA methylation, we utilized a TET1 catalytic
20 domain (TET1CD)-mediated targeted DNA demethylation lentivirus system which
21 has efficiently converted NPCs fate into astrocytes by targeting the methylation status
22 of GFAP promoter(Morita et al., 2016). Single guide RNAs (sgRNAs) targeting

1 sequences near each of three NBREs were incorporated into the vector (Fig. 4G).
2 MeDIP experiment confirmed that sgNBRE-1 was the most potent guide RNA that
3 was able to induce decreased levels of 5mC at and near the targeting region in DA
4 progenitors (Fig. 4H). Co-introducing sgNBRE-1 with MeCP2 into DA NPCs
5 attenuated the repression of *Th* expression (Fig. 4I). Furthermore, ChIP analysis
6 demonstrated that sgNBRE-1 caused decreased MeCP2 binding and increased
7 NURR1 binding on the first NBRE in the context of MeCP2 overexpression (Fig. 4J).
8 Taken together, these results indicate that prematurely-expressed MeCP2
9 preferentially bound to hypermethylated promoters of DA phenotype genes in DA
10 NPCs, thereby preventing DA subtype specification through interfering
11 TET1-mediated DNA de-methylation.

12

13 **Tet1 counteracts MeCP2 to maintain DA phenotype in DA neurons.**

14 As demonstrated above, the *Th* promoter in DA neurons was hypomethylated in
15 comparison to that in DA NPCs, and it permitted no further enrichment of MeCP2
16 when overexpressed in DA neurons. These results appeared to suggest an association
17 of DNA hypomethylation with the constitutive expression of DA phenotype genes in
18 DA neurons. Opposite to its role as a global transcriptional repressor in NPCs, recent
19 studies have revealed MeCP2 as a global activator in differentiated neurons. An
20 intriguing question is whether the role of MeCP2 as a transcriptional repressor of DA
21 phenotype genes is retained during DA neuronal differentiation. To validate this, we
22 employed a well-defined shRNA-mediated TET1 inhibition (He et al., 2015) to

1 prevent the transition of 5mC to 5hmC in differentiating DA neurons after the DA
2 subtype specification (from DIV4). MeDIP analysis demonstrated that TET1
3 knockdown caused efficient DNA methylation on *Th* promoter (Fig. 5A), suggesting
4 that TET1 was responsible for not only the conversion but also the maintenance of
5 DNA hydroxymethylation. Concomitantly, MeCP2 enrichment was significantly
6 increased at NBRE-1. Overexpression of MeCP2 further exacerbated this recruitment
7 (Fig. 5B). As a consequence, enrichment of NURR1 was reduced (Fig. 5C), and gene
8 expression of *Th* was compromised (Fig. 5D).

9

10 Using a luciferase reporter assay, we previously have shown that *Th* gene expression
11 is extremely sensitive to CpG methyltransferase MQ1-induced DNA methylation. To
12 exclude the overall regulation effect of sh-TET1, we employed an inactive
13 Cas9-mediated targeted DNA methylation system involving MQ1 and its mutant
14 MQ1^{147L} with better enzyme activity (Lei et al., 2017) to manipulate targeted
15 methylation of *Th* promoter in DA neurons. Based on targeted de-methylation results
16 above, we focused on sgRNA targeting NBRE-1. MQ1 and MQ1^{147L} successfully
17 caused more than 50% *Th* gene silencing in MeCP2-overexpressed DA neurons (Fig.
18 5E). MeDIP analysis of NBRE-1 region confirmed that 5mC was enriched by
19 sg-NBRE-1 guided MQ1 and MQ1^{147L} (Fig. 5F). As a consequence, ChIP analysis
20 demonstrated an increased recruitment of MeCP2 onto NBRE-1 in DA neurons
21 experiencing overexpressed MeCP2 and MQ1-mediated targeted methylation (Fig.
22 5G). These results support the notion that MeCP2 functions as a transcriptional

1 repressor that specifically recognizes methylated CpG sites in both DA NPCs and DA
2 neurons. Conversely, decreased recruitments of TET1 and NURR1 were detected at
3 NBRE-1 region (Fig. 5H and 5I), suggesting a counteracting role of MeCP2 with
4 transcription activators of DA phenotype genes.

1 **Discussion**

2 Here we performed a series of gain-of-function experiments to investigate the effects
3 of abnormal timing of MeCP2 expression on midbrain DA neurogenesis, particularly
4 on the acquisition and maintenance of DA subtype. Evidence exist for a long time in
5 attempt to establish a direct link between MeCP2 and catecholamine system in CNS
6 (Nomura et al., 1985). For instance, abnormal concentrations of biogenic amines have
7 been observed in brains of MeCP2-null mouse and cerebrospinal fluid of Rett
8 syndrome patients (Roux and Villard, 2010). However, these alterations are supposed
9 to be independent of prenatal DA neuron development, as MeCP2-knockout
10 embryonic stem cells are capable of differentiating into TH-expressing DA neurons in
11 vitro (Okabe et al., 2010), and rescue of MeCP2 expression in Rett syndrome mice in
12 postnatal stage rectified neuronal and behavior defects (Lang et al., 2013; Robinson et
13 al., 2012). Based on these loss-of-function studies, it seems reasonable to conclude
14 that the major role of MeCP2 is to maintain DA neuron function after neuronal
15 differentiation. However, despite of their similar postnatal behavioral deficits, little is
16 known about whether MeCP2 loss-of-function and gain-of-function share similar
17 developmental pathways and molecular mechanisms. Our findings provide
18 compelling in vitro evidence for a novel role of MeCP2 in DA neuron differentiation,
19 proposing that controlling the timing and restricting the expression level of MeCP2 in
20 DA NPCs is necessary for DA subtype specification. This information could be
21 further exploited to induce efficient generation of functional DA neurons in the
22 purpose of stem cell therapy and regenerative medicine. On the other hand, the

1 gain-of-function of MeCP2 is genetically correlated with MeCP2 duplication or
2 triplication syndrome. It remains to be determined whether precocious expression of
3 MeCP2 indeed occurs in patients with these syndromes and MeCP2-overexpressing
4 mice.

5

6 MeCP2 functions as transcriptional activator or repressor depending on genes and
7 regulatory context (Chahrour et al., 2008). Our data support the notion that MeCP2 is
8 a transcriptional repressor for DA phenotype genes regardless of developmental stage.

9 This is consistent with previous studies that identified *Th* and *Aadc* as direct target
10 genes of MeCP2 (Urdinguio et al., 2008; Yang et al., 2011). Furthermore, MBD and
11 TRD are both indispensable for MeCP2-mediated repression, as preventing DNA
12 binding of MeCP2 or overexpressing TRD mutation R168X failed to repress *Th* gene
13 expression. The function of MBD determines whether or not MeCP2 is recruited to
14 DNA sequences, allowing TET1-mediated de-methylation to distinguish DNA
15 binding of MeCP2 in DA NPCs and DA neurons. The function of TRD is to recruit
16 other repressive complexes, so as to block the recruitment of other activators such as
17 NURR1 and TET1. Interestingly, one study using MeCP2-overexpressing mice
18 demonstrate that the duplication toxicity requires both domains to be functional
19 (Heckman et al., 2014), raising the possibility that too much MeCP2 protein might
20 function as a universal transcriptional repressor rather than activator.

21

22 The molecular mechanisms proposed here raise at least two neuropathological

1 concerns (Fig. 6). First is the premature MeCP2 expression in DA NPCs. We
2 previously have shown that the promoter regions of other DA phenotype genes such
3 as *Aadc* and *Dat* were also hypermethylated like *Th* in DA NPCs (He et al., 2015),
4 and the expression of these genes are also under transactivation of NURR1 (van
5 Heesbeen et al., 2013). It is possible that the mode of action of premature MeCP2
6 expression proposed here is applicable to other DA phenotype genes, affecting a
7 wider range of DA neuronal functions including DA synthesis, transport and
8 re-uptake. Second is failed de-methylation of DA phenotype genes in DA neurons. In
9 Figure 5, MeCP2 overexpression in DA neurons enhanced the gene repression effect
10 induced by targeted methylation of *Th* promoter, suggesting that the maintenance of
11 DA phenotype genes in DA neurons is sensitive to DNA methylation. As MeCP2 is
12 highly expressed in adult midbrain DA neurons, genetic deficiency such as TET1
13 mutation or environmental cues that induce DNA methylation might work as potential
14 risk factors for the proper functioning of midbrain DA neurons. However, although
15 DNA methylation was induced in both MeCP2-overexpressed and normal DA neurons,
16 the transcription of *Th* gene was only repressed in MeCP2-overexpressed DA neurons.
17 Consistently, DNA bindings of repressors and activators were also not altered in
18 normal DA neurons experiencing MQ1-mediated targeted DNA methylation. These
19 results might suggest the existence of an unidentified regulation mode that protects
20 DA neurons from DNA methylation-related gene silencing.

1 **Materials and Methods**

2 **Cell culture**

3 DA NPCs were extracted from ventral regions of mouse E10.5 mesencephalon,
4 mechanically dissociated into single cells and plated onto poly-L-ornithine and
5 fibronectin double-coated glass coverslips and culture plates. Cells were allowed for
6 proliferation by daily addition of basic fibroblast growth factor and epidermal growth
7 factor in Neurobasal media supplemented with N2 and B27 supplement. DA neuron
8 differentiation was conducted by withdrawal of mitogens from culture media for 3 to
9 6 days. For NURR1 overexpression experiments, NPCs were extracted from rat
10 embryonic day 13 cortices and cultured by similar approach to mouse DA progenitors,
11 except that only basic fibroblast growth factor was used for proliferation and B27
12 supplement was not included in the media. All culture media were changed every
13 other day and cells were maintained at 37°C in humidified 5% CO₂ incubators.

14

15 **Plasmids and gene delivery**

16 cDNAs encoding full length mouse MeCP2 and NURR1 was generated by reverse
17 transcriptase-PCR from RNA extracted from adult mouse brain. Plasmid expressing
18 Dx-inducible MeCP2 was made by cloning the cDNA into FUW-TetO-MCS vector
19 (Addgene plasmid #84008). Plasmid expressing MeCP2 and GFP tagging was made
20 by cloning the cDNA into pLVX-EF1 α -IRES-ZsGreen1 vector (TaKaRa plasmid
21 #631982). R168X mutation was introduced by site-directed mutagenesis. Plasmid
22 expressing NURR1 was made by cloning the cDNA into pLVX-based vector. Plasmid

1 expressing rat-specific shTET1 was purchased from Origene (#309902). For targeted
2 DNA de-methylation, sgRNAs were cloned into pPlatTET-gRNA2 vector (Addgene
3 plasmid #82559). Plasmids expressing sgRNAs were made by cloning the annealed
4 oligo sgRNA sequences into PX459-based vector (Addgene plasmid #62988). The
5 oligo sequences for sg-NBRE-1, -2, -3 are 5'-GAGGGGCTTGACGTCAGCC-3',
6 5'-AATTAGATCTAATGGGACGG-3', 5'-ACTTTGTTACATGGGCTGGG-3',
7 respectively.

8 For the production of viruses, the virus vectors and 2nd generation packaging vectors
9 were introduced into HEK293T packaging cell line by transient transfection with
10 Lipofectamine 2000 (Invitrogen). One day later, supernatants were harvested,
11 concentrated with PEG8000 (Sigma), and stored until use. For viral transduction, cells
12 were incubated with the viral supernatant containing polybrene (4 µg/ml, Sigma) for 6
13 hours.

14 For targeted DNA methylation, MQ1 and MQ1^{Q147L} plasmids (Addgene plasmid
15 #89634, 89637) and sgRNAs were co-transfected into DA neurons with
16 Lipofectamine Stem (Invitrogen) for 6 hours.

17

18 **Immunofluorescent staining and imaging**

19 Cells were fixed with 4% paraformaldehyde for 20 minutes, permeabilized and
20 blocked with phosphate buffered saline with 0.3% Triton-X100 and 1% bovine serum
21 albumin for 40 minutes, then incubated with first antibodies diluted with blocking
22 solution at 4°C overnight. Alexa Fluo series of second antibodies (Thermo Scientific)

1 were applied accordingly for two hours at room temperature. Cells were finally
2 mounted in 4',6-diamidino-2-phenylindole (DAPI) and examined using fluorescence
3 microscope (Leica DMi8). Embryonic and postnatal ventral midbrain tissues were
4 fixed with 4% paraformaldehyde and dehydrated with 30% sucrose overnight, and
5 cryosectioned at 14 μ m thickness. The first antibodies used include rabbit anti-MeCP2
6 (Cell Signaling Technology), mouse anti-NURR1 (R&D Systems), mouse anti-TH
7 (Sigma), rabbit anti-NURR1 (Santa Cruz Biotechnology).

8

9 **Real-time PCR analysis**

10 RNA was extracted, reverse-transcribed (TaKaRa), amplified, and applied to real-time
11 PCR analyses (Roche). The comparative cycle threshold method was used for
12 quantification. Each experiment was repeated at least once to guarantee same trend of
13 gene expression. Data from one experiment was used to generate representative
14 histogram. The primer sequences are listed in Supplemental Table 1.

15

16 **ChIP, MeDIP and hMeDIP**

17 For ChIP experiments, cells were cross-linked with 1% paraformaldehyde for 15
18 minutes and Chromatins were sheared into an average 200–400 bp in length by
19 sonication (Diagenode) and immunoprecipitated with following antibodies: rabbit
20 anti-MeCP2 (Cell Signaling Technology), rabbit anti-NURR1 (Santa Cruz
21 Biotechnology) and rabbit anti-TET1 (Abcam). Immunoprecipitated DNA fragments
22 were collected by magnetic beads (Active Motif), purified, and subjected to real-time

1 PCR using primers specific to regions spanning three NBREs on *Th* promoter. Data
2 were normalized to values of the input DNA. For MeDIP and hMeDIP experiments,
3 genomic DNA were extracted from cells, sheared, immunoprecipitated, collected and
4 subjected to real-time PCR in a similar way as ChIP with following antibodies: mouse
5 anti-5mC (Abcam) and rabbit anti-5hmC (Active Motif). The primers are listed in
6 Supplemental Table 1.

7

8 **Cell counting and statistics**

9 Immunoreactive or DAPI-stained cells were counted in at least 10 random regions of
10 each culture coverslip using an eyepiece grid at a magnification of 50 to 400X. Data
11 are expressed as mean \pm S.E.M. of three to five independent cultures. Statistical
12 comparisons were made using Student's t-test or one-way ANOVA with Tukey's post
13 hoc analysis (Graphpad Prism).

1 **Competing Interest Statement**

2 The authors declare no competing interests.

3

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6 [31701287 to X-B.H.].

7

8 **Author Contributions**

9 X-B.H. conceived the study and wrote the manuscript. X-B.H. performed cell culture,

10 immunostaining and epigenetic experiments. F.G. performed molecular cloning, virus

11 production, PCR experiments and helped with data collection and data analysis. K.L.

12 and J.Y. were involved in data analysis and figure arrangement. S-H.L. provided

13 technique support and supervised epigenetic experiments. All authors have read and

14 approved the final version of the manuscript.

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- 32

1 **Figure legends**

2 **Figure 1.** Expression patterns of NURR1, MeCP2 and TH in developing and adult
3 mouse midbrains and cell model of embryonic mouse midbrain dopamine (DA)
4 neuron differentiation. (A) Sagittal (Embryonic day (E) 10.5) and coronal (E12.5 and
5 Postnatal day (P) 28) views of MeCP2-positive cells co-express NURR1 or TH in
6 mouse ventral midbrains. TH is not detected at E10.5. Both ventral tegmental area
7 (VTA) and substantia nigra (SN) of midbrain is shown at P28. Scale bar represents
8 100 μ m. A summary of the expression patterns in vivo is depicted in (B). (C) Cultured
9 DA neural precursor cells (NPCs) were allowed for 6 days of DA neuronal
10 differentiation in vitro (DIV). DIV 0, 3 and 6 were selected for immunofluorescent
11 labeling of cells expressing NURR1/MeCP2 and TH/MeCP2. Scale bar represents 20
12 μ m. A summary of the expression patterns in vitro is depicted in (D).

13

14 **Figure 2.** Overexpressing MeCP2 in different periods of dopamine (DA) neuron
15 differentiation. (A) Schematic overview depicting time- and dose-dependent
16 overexpression of MeCP2 by FUW-TetO-mMeCP2 lentivirus within 6 days of DA
17 neuronal differentiation in vitro (DIV). Two concentrations of Doxycycline (Dx) were
18 treated from early (DIV 1-3) or late (DIV 4-6) period of differentiation, in which DA
19 subtype was specified and maintained, respectively. (B) Representative images and
20 quantification of percentage of cells expressing DA subtype marker tyrosine
21 hydroxylase (TH) after 6 days of differentiation. (C) Transcriptional changes of DA
22 phenotype genes *Th* and *Aadc* in response to MeCP2 overexpression. 2 μ M Dx was

1 added within DIV 1-3 or DIV 4-6. Analysis was performed DIV 6. One representative
2 data from three independent experiments is shown. Data are expressed as mean \pm S.D.
3 (D) Representative images and quantification of percentage of cells expressing TH
4 showing that overexpression of MeCP2 and its transcription repression domain
5 mutation R168X in cultured DA neural precursor cells (NPCs) have different impact
6 on DA subtype specification. Ectopic genes were delivered by lentiviruses carrying
7 ZsGreen1 fluorescent protein (GFP). (E) Quantification of cells double positive for
8 TH and GFP. Note that no double positive cells in MeCP2-overexpressed group,
9 indicating no cells overexpressing MeCP2 acquired DA phenotype after
10 differentiation. Scale bar represents 50 μ m. Cell numbers were counted in 10 random
11 areas of each culture coverslip. Data represent mean \pm S.E.M. n=3 independent
12 culture. * $P < 0.05$, ns, not significant; one-way ANOVA with Tukey's post hoc
13 analysis.

14

15 **Figure 3.** Roles of MeCP2 in NURR1-mediated transactivation of dopamine (DA)
16 phenotype genes. (A, B) Rat cortical neural precursor cells (NPCs) were transduced
17 with NURR1, NURR1+MeCP2 and NURR1+R168X and allowed for spontaneous
18 differentiation for 3 days. R168X is a truncated mutation of MeCP2 which does not
19 contain transcription repression domain. ZsGreen1 fluorescent protein (GFP) marks
20 cells transduced with MeCP2, R168X or control vector. Representative images and
21 quantification of cells expressing TH are shown as (A) and (B), respectively. (C)
22 Quantification of MeCP2 or R168X-transduced cells expressing TH. (D)
23 Transcriptional repression of NURR1-mediated expression of DA phenotype genes by
30

1 MeCP2 but not R168X. (E) Schematic of 1kilo bp length of rat *Th* promoter and
2 locations of three Nurr1 binding sites (NBREs). (F-I) Chromatin immunoprecipitation
3 (ChIP) analyses were performed to measure the DNA binding of MeCP2 (F and H)
4 and of NURR1 (G and I) onto NBREs in DA NPCs and DA neurons transduced with
5 MeCP2 or R168X. For ChIP assays, one representative data from two independent
6 experiments is shown. Data are expressed as mean \pm S.D. Scale bar represents 20 μ m.
7 For immunostaining experiments, cell numbers were counted in 10 random areas of
8 each culture coverslip. Data represent mean \pm S.E.M. n=3 independent culture. * $P <$
9 0.05, ns, not significant; one-way ANOVA with Tukey's post hoc analysis.

10

11 **Figure 4.** DNA de-methylation in dopamine neural precursor cells (DA NPCs)
12 prevents MeCP2 overexpression-induced transcriptional repression of DA phenotype
13 genes. (A) DNA methylation (5mC) and hydroxymethylation (5hmC) states within
14 1kilo bp promoter region of DA phenotype gene *Th* at differentiation day (DIV) 0 and
15 DIV 6. (B) Chromatin immunoprecipitation (ChIP) experiment showing increased
16 TET1 recruitment onto three NURR1 binding sites (NBREs) within *Th* promoter
17 along with differentiation. (C) Doxycycline (Dx)-induced overexpression of MeCP2
18 in DA progenitors caused DNA methylation of *Th* promoter after DA neuronal
19 differentiation. (D) TET1 recruitment onto NBREs within *Th* promoter at DIV 6 was
20 reduced by overexpression of MeCP2 in DA NPCs. (E) Quantification of TH+ cells at
21 DIV 6. Vitamin C (VC) was added in DA NPCs overexpressing MeCP2 or truncated
22 mutation R168X from DIV 0 to DIV 6. Data represent mean \pm S.E.M. n=3

1 independent culture. * $P < 0.05$, ns, not significant; one-way ANOVA with Tukey's
2 post hoc analysis. (F) Enrichment of MeCP2 onto NBREs is reduced by VC in
3 MeCP2-overexpressed DA NPCs. (G) Schematic showing strategy of targeted
4 recruitment of inactive Cas9-TET1 catalytic domain (dCas9-TET1CD) guided by
5 small guiding RNAs (sgRNAs) onto three NBREs within *Th* promoter. (H) Targeted
6 de-methylation guided sgRNA targeting the first NBRE on *Th* promoter (sg-NBRE-1)
7 in DA NPCs caused decreased DNA methylation at and near local DNA regions after
8 differentiation. (I) Effect of targeted de-methylation of NBRE-1 in DA NPCs with or
9 without MeCP2 overexpression on gene expression of *Th* after differentiation. (J)
10 ChIP experiments showing the effect of targeted de-methylation of NBRE-1 in DA
11 NPCs with or without MeCP2 overexpression on recruitments of MeCP2 and NURR1
12 onto NBRE-1 after differentiation. One representative data from two independent
13 experiments is shown. Data are expressed as mean \pm S.D.

14

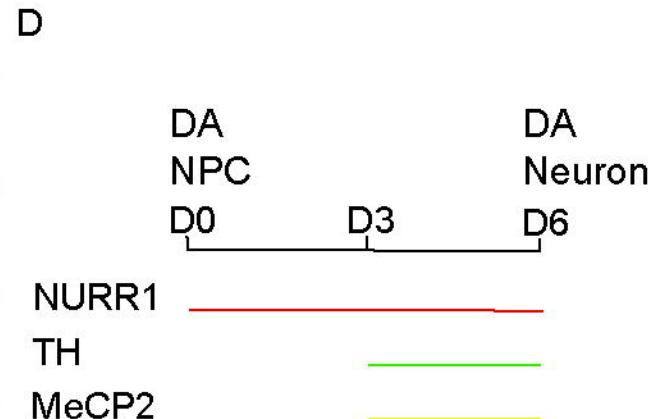
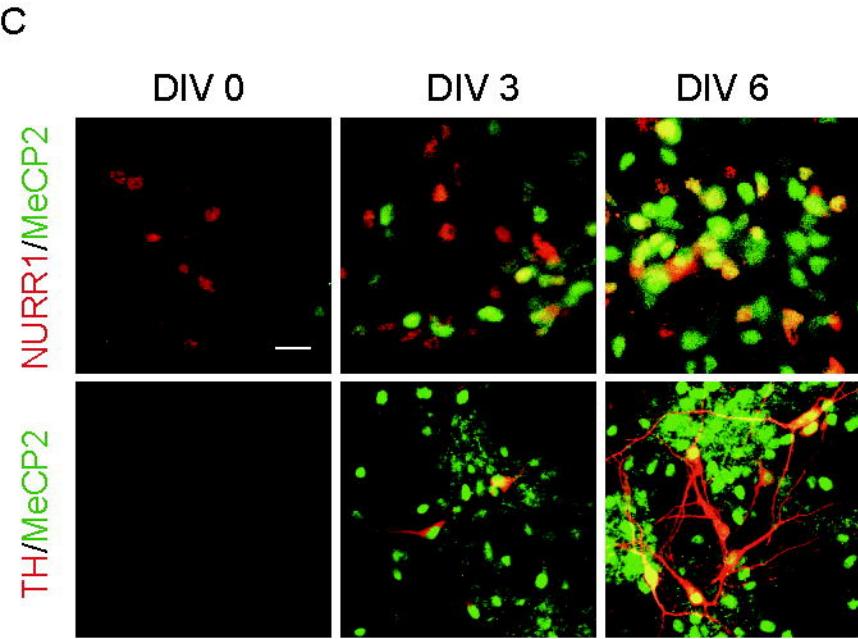
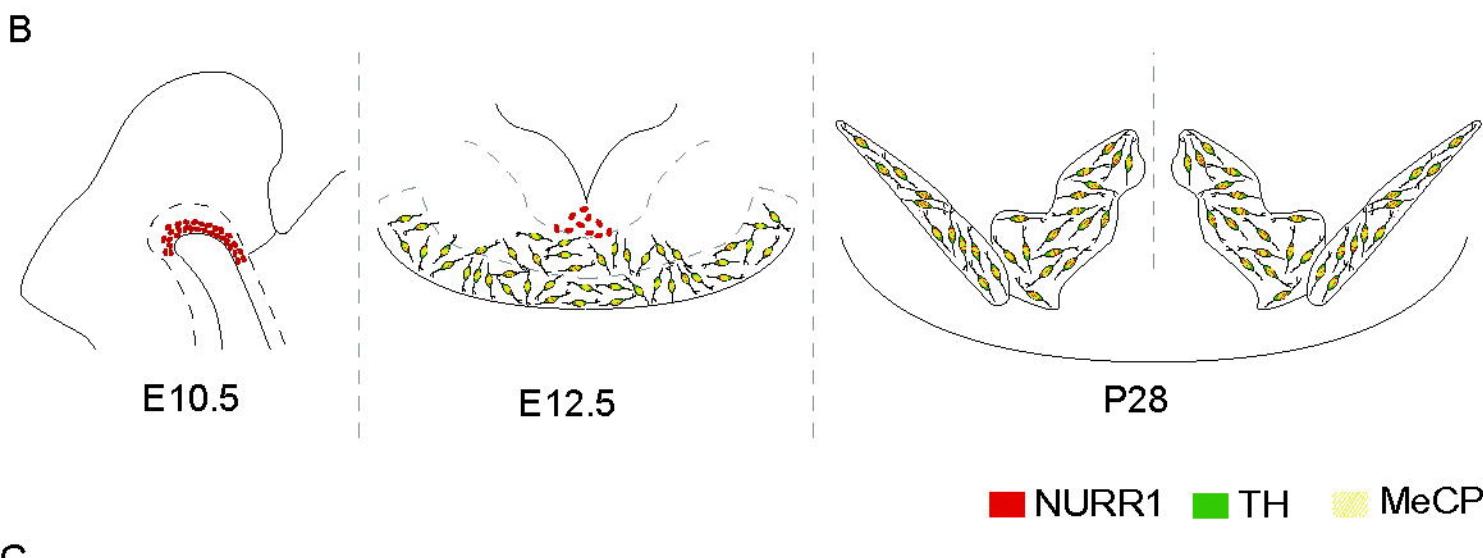
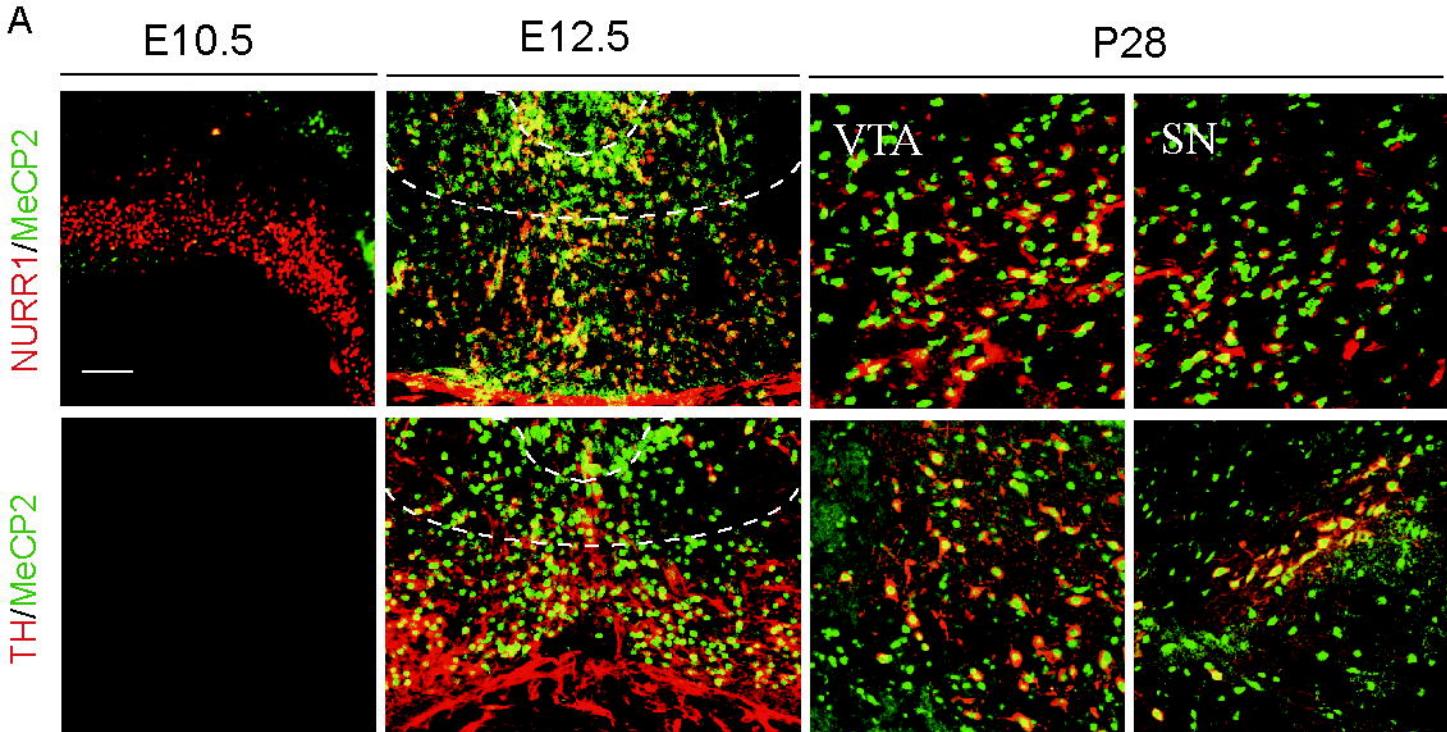
15 **Fig 5.** Targeted DNA methylation in dopamine (DA) neurons permits overexpressed
16 MeCP2 counteracting TET1-dependent DA subtype maintenance. (A) Inhibition of
17 TET1 by short hairpin RNA in DA neurons causes DNA methylation of *Th* promoter.
18 (B and C) Effect of TET1 inhibition on recruitment of MeCP2 (B) and NURR1 (C)
19 onto the first NURR1 binding site (NBRE-1) in DA neurons with or without MeCP2
20 overexpression. (D) Effect of TET1 inhibition on *Th* gene expression in DA neurons
21 with or without MeCP2 overexpression. (E and F) Targeted recruitments of
22 dCas9-MQ1 and its activity-enhancing mutation MQ1^{147L} onto NBRE-1 within *Th*

1 promoter in normal or MeCP2-overexpressed DA neurons showed different impact on
2 *Th* gene expression (E) and DNA methylation (F). (G-I) Effects of targeted DNA
3 methylation of NBRE-1 in normal or MeCP2-overexpressed DA neurons on
4 recruitments of MeCP2 (G), TET1 (H) and NURR1 (I) onto NBRE-1. One
5 representative data from two independent experiments is shown. Data are expressed
6 as mean \pm S.D.

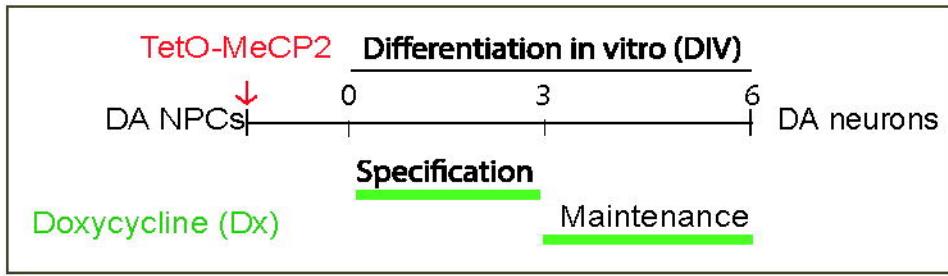
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8 **Fig 6.** Proposed model illustrating mechanisms underlying differential effects of
9 timing and dose of MeCP2 expression on dopamine (DA) subtype specification and
10 maintenance during midbrain DA neurogenesis. *Th* serves as a representative for DA
11 phenotype genes. (A) Under normal development, DA subtype is not yet specified in
12 DA neural precursor cells (NPCs) due to hypermethylation of the promoters of DA
13 phenotype genes and lack of NURR1. Along with differentiation, TET1 induces
14 gene-specific DNA de-methylation, in particular of NURR1 binding sites (NBREs),
15 which allows recruitment of NURR1 for gene transactivation. The expression of DA
16 phenotype genes is maintained after differentiation in DA neurons. (B) MeCP2 is
17 normally not expressed in DA NPCs before subtype specification. When MeCP2 is
18 prematurely expressed, for instance, in MeCP2 duplication syndrome, the
19 hypermethylated promoters of DA phenotype genes become targets for MeCP2
20 recruitment and its mediated gene repression. This prevents TET1-mediated DNA
21 de-methylation of DA phenotype genes along with DA neuronal differentiation. As a
22 consequence, DA NPCs and neurons after differentiation are not able to acquire DA

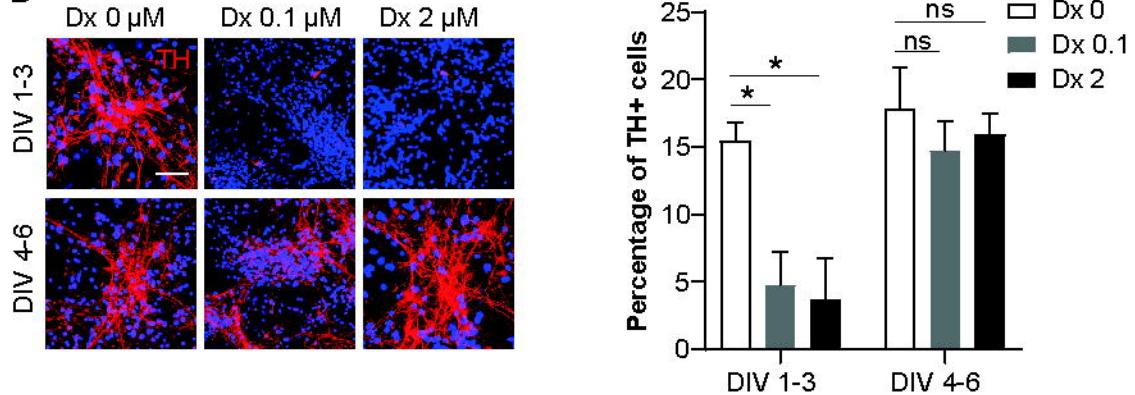
1 subtype. (C) In DA neurons, TET1 continues de-methylating DA phenotype genes,
2 allowing constitutive NURR1 binding and maintenance of DA phenotype. TET1
3 dysfunction leads to hypermethylation of DA phenotype genes, allowing binding of
4 excess MeCP2, failed NURR1 binding and subsequent loss of DA subtype.



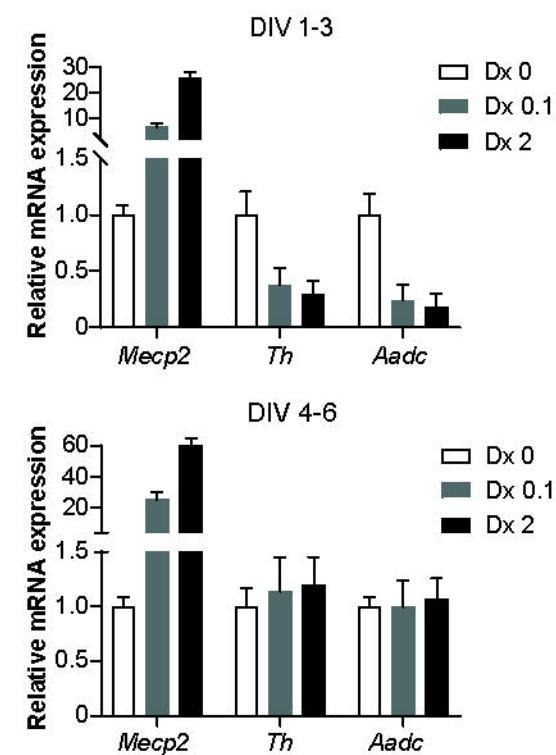
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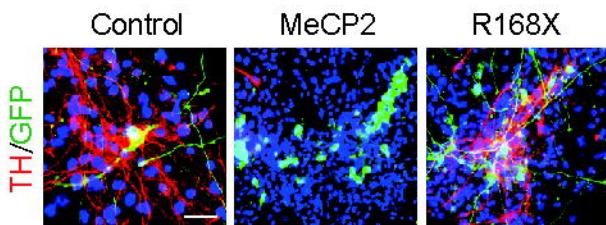
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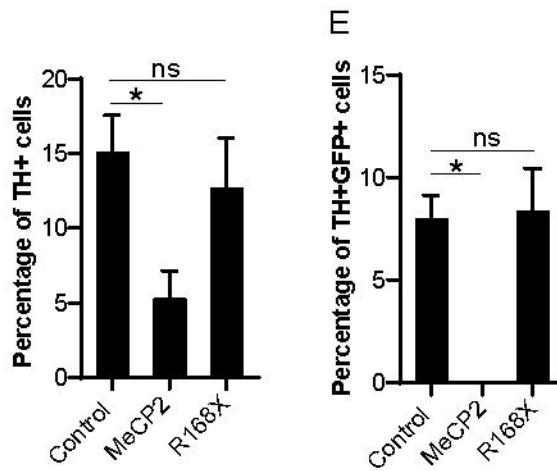
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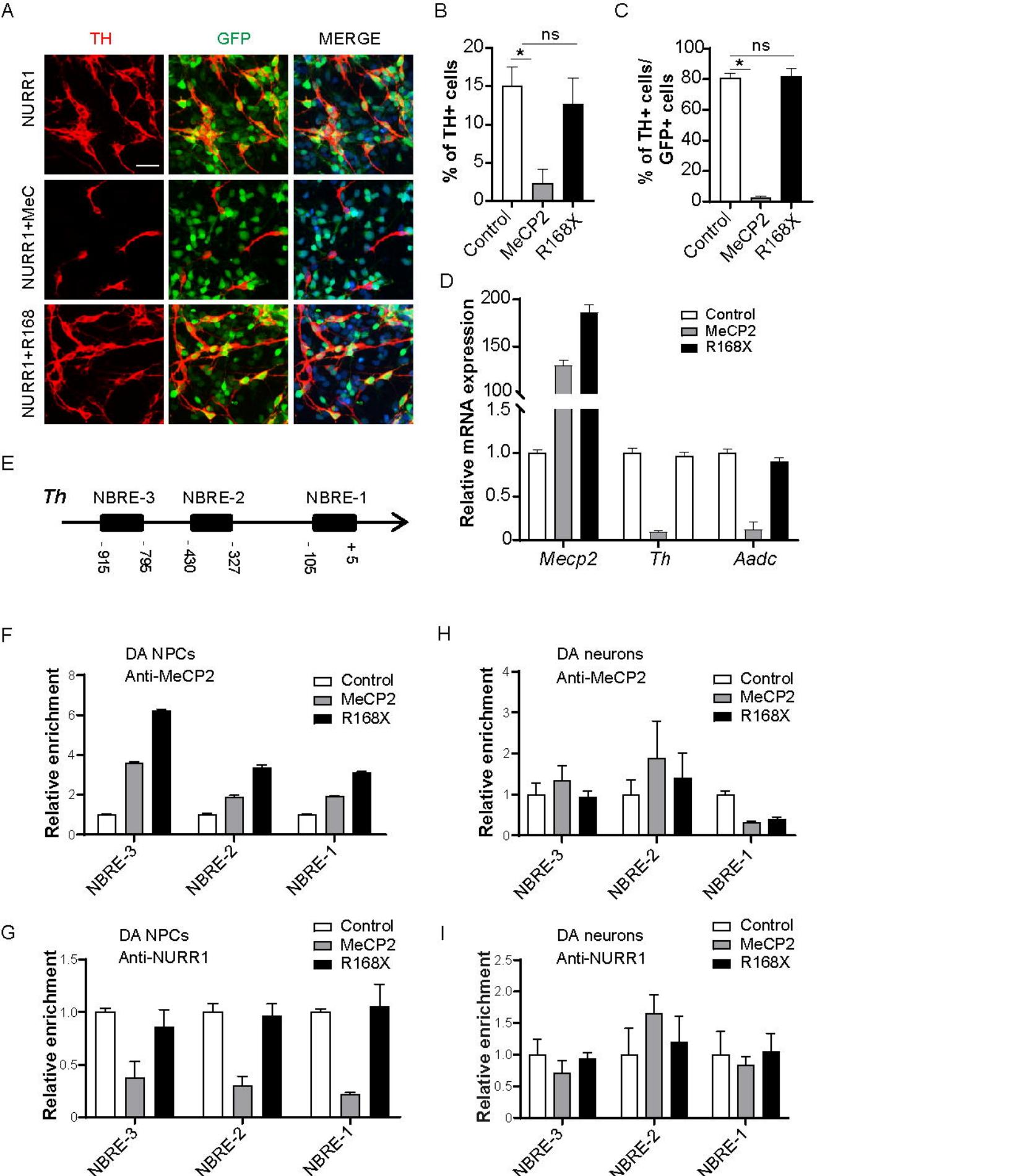


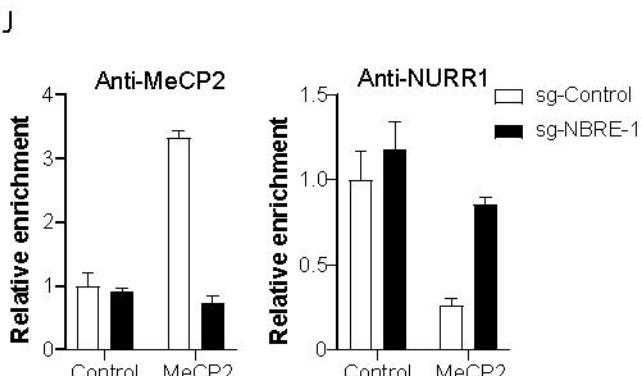
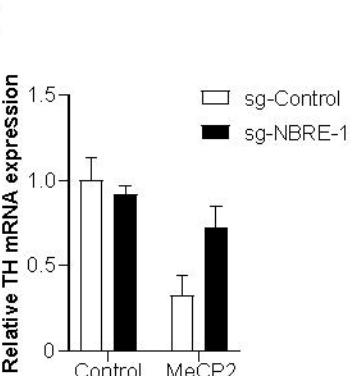
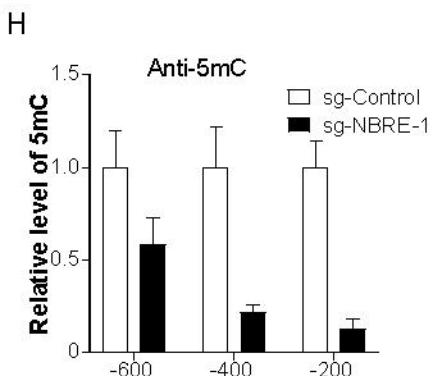
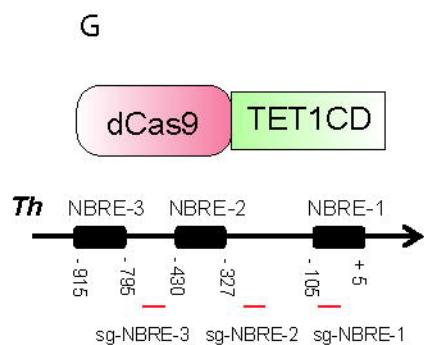
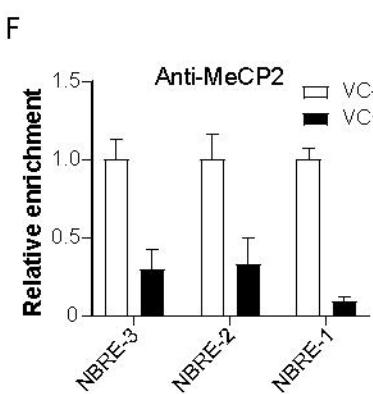
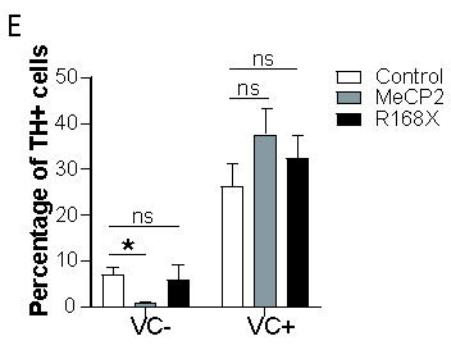
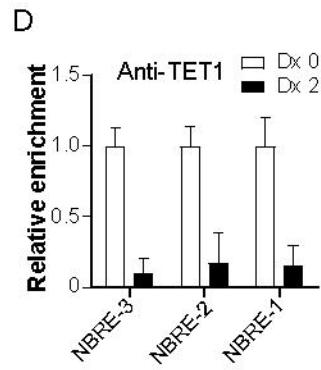
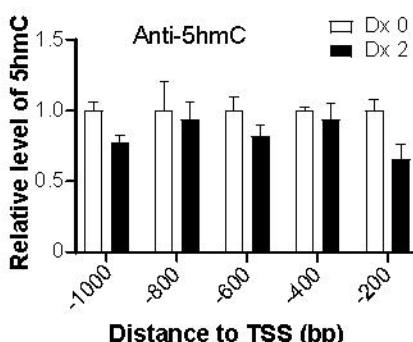
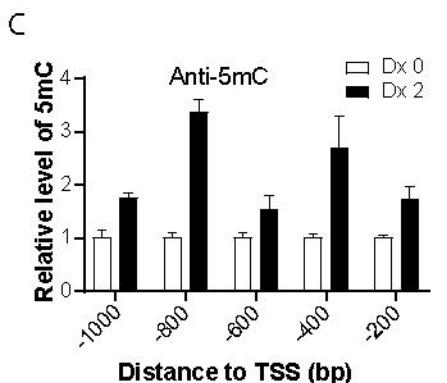
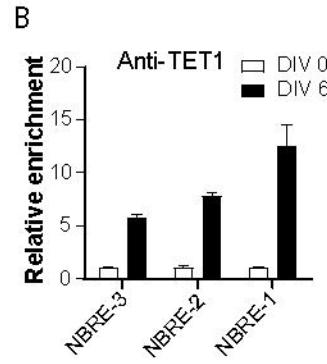
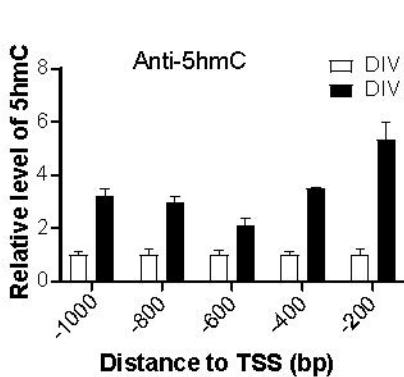
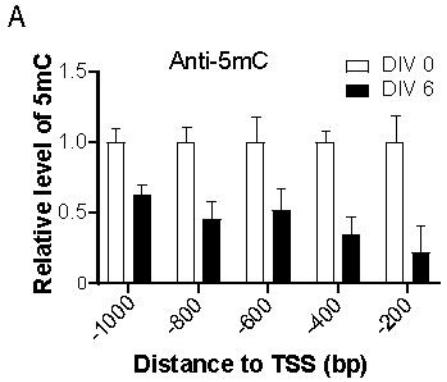
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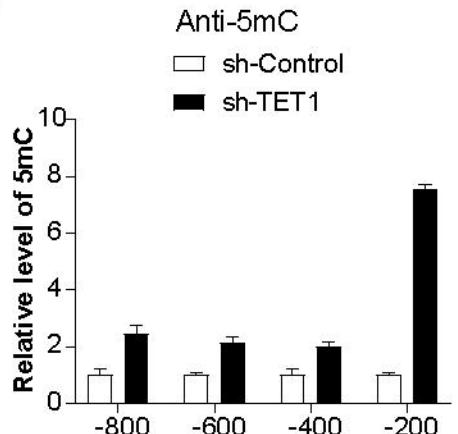
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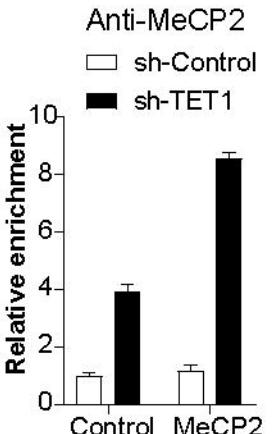




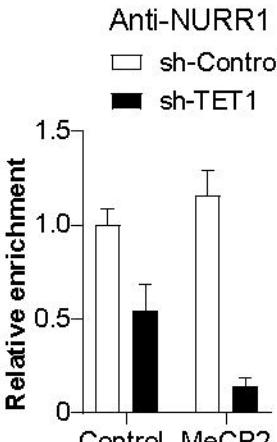
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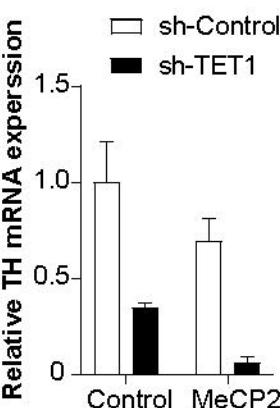
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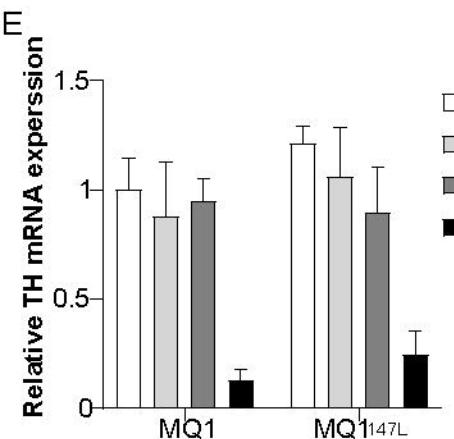
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D

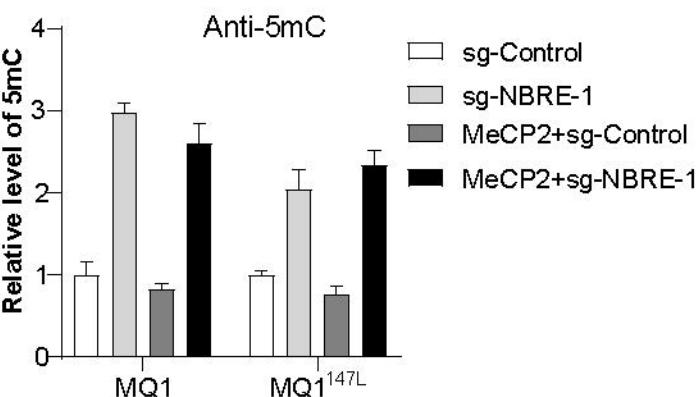


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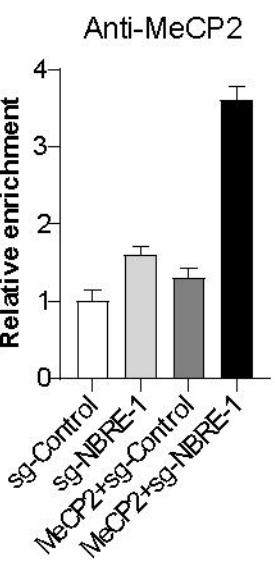


sg-Control
sg-NBRE-1
MeCP2+sg-Control
MeCP2+sg-NBRE-1

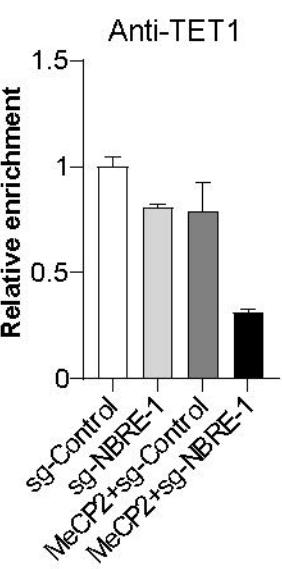
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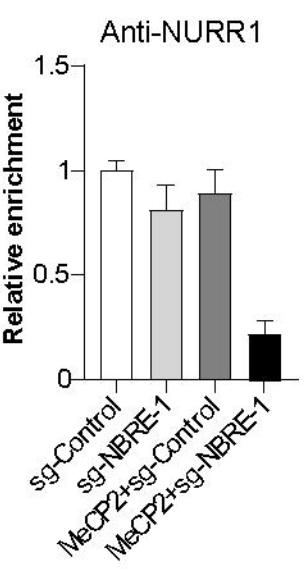
G



H



I



sg-Control
sg-NBRE-1
MeCP2+sg-Control
MeCP2+sg-NBRE-1

(A) Normal DA neurogenesis

