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# Zinc finger genes *Fezf1* and *Fezf2* control neuronal differentiation by repressing *Hes5* expression in the forebrain

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## SUMMARY

Precise control of neuronal differentiation is necessary for generation of a variety of neurons in the forebrain. However, little is known about transcriptional cascades, which initiate forebrain neurogenesis. Here we show that zinc finger genes *Fezf1* and *Fezf2*, which encode transcriptional repressors, are expressed in the early neural stem (progenitor) cells and control neurogenesis in mouse dorsal telencephalon. *Fezf1*- and *Fezf2*-deficient forebrains display upregulation of *Hes5* and downregulation of neurogenin 2, which is known to be negatively regulated by *Hes5*. We show that FEZF1 and FEZF2 bind to and directly repress the promoter activity of *Hes5*. In *Fezf1*- and *Fezf2*-deficient telencephalon, the differentiation of neural stem cells into early-born cortical neurons and intermediate progenitors is impaired. Loss of *Hes5* suppresses neurogenesis defects in *Fezf1*- and *Fezf2*-deficient telencephalon. Our findings reveal that *Fezf1* and *Fezf2* control differentiation of neural stem cells by repressing *Hes5* and, in turn, by derepressing neurogenin 2 in the forebrain.

**KEY WORDS: Corticogenesis, Neurogenesis, Zinc finger genes, *Fezf1*, *Fezf2*, *Hes5*, neurogenin 2, Mouse**

## INTRODUCTION

The mammalian forebrain is the most complex and organized structure that contains a variety of neurons and glia and that is required for higher neuronal functions, including memory, reasoning, emotion and planning. During development of the mammalian dorsal telencephalon (neocortex), neurons are generated sequentially from neural stem (progenitor) cells located in the ventricular zone (VZ) (Molyneaux et al., 2007). In mice, the Cajal-Retzius (CR) cells and subplate (SP) neurons are born around embryonic day (E) 11.5 or earlier (Allendoerfer and Shatz, 1994; McConnell et al., 1989). Layers VI (corticothalamic), V (subcerebral projection), IV, and II-III (intercortical projection) are then generated in the VZ around E12.5, E13.5, E14.5 and E15.5, respectively, and migrate to appropriate cortical layers (Leone et al., 2008; Molyneaux et al., 2007). Recent studies have identified transcription factors and gene networks that control specification of these cortical neurons (Alcamo et al., 2008; Arlotta et al., 2008; Britanova et al., 2008; Chen et al., 2005a; Chen et al., 2008; Hevner et al., 2001; Molyneaux et al., 2005; Zhou et al., 1999). It is thought that differentiation of the cortical neurons from the neural stem cells takes place in the VZ through asymmetric cell divisions (Chenn and McConnell, 1995; Gotz and Huttner, 2005). At least some cortical neurons are also differentiated from the TBR2$^{+}$ intermediate progenitors (also called basal progenitors; EOMES – Mouse Genome Informatics), which are derived from the neural stem cells in the VZ (Arnold et al., 2008; Kowalczyk et al., 2009; Sessa et al., 2008). However, little is known about the molecular mechanisms by which the neural stem cells are differentiated into neurons or intermediate progenitors during early cortical development.

Hes genes are vertebrate homologs of *Drosophila hairy* and *enhancer of split*, which encode basic helix-loop-helix (bHLH) transcriptional repressors, and Hes proteins function to repress the expression of the bHLH proneural genes, which promote neurogenesis (Kageyama et al., 2007; Kageyama et al., 2008a; Ross et al., 2003). *Hes1*, *Hes3* and *Hes5* are expressed in the neural stem cells of the central nervous systems of mice and their loss results in acceleration of neuronal differentiation and depletion of the neural stem cells (Hatakeyama et al., 2004). Hes genes are known as downstream effectors of Notch signaling (Ohtsuka et al., 1999), and deficiency of Notch signal components leads to precocious neuronal differentiation from the neural stem cells (Gaiano and Fishell, 2002; Louvi and Artavanis-Tsakonas, 2006; Yoon and Gaiano, 2005). Thus, the Notch-Hes pathway plays an essential role in the maintenance of the neural stem cells. However, it remains elusive how the Notch-Hes pathway is controlled during the cortical development.

*Fezf1* (*Fez*) and *Fezf2* (*Fez-like*, *Zfp312*) are closely related genes that encode transcriptional repressors containing six C2H2-type zinc fingers and an EH1 (Engrailed homology 1) repressor motif, which is known to interact with Groucho or Tle (Transducin-like enhancer of split)-type transcriptional co-repressors (Shimizu and Hibi, 2009). Both *Fezf1* and *Fezf2* are expressed in the prospective forebrain region during early embryogenesis and they subsequently exhibit both overlapping and distinct expression domains in the mouse forebrain (Chen et al., 2005b; Hirata et al., 2006a; Hirata et al., 2006b; Hirata et al., 2004). Loss-of-function studies in mice reveal that *Fezf1* is involved in development of the olfactory sensory system (Hirata et al., 2006b) and that *Fezf2* is not only involved in

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the differentiation of SP neurons (Hirata et al., 2004) but also essential for specification of the subcerebral projection neurons in layer V of the cortex (Chen et al., 2005a; Chen et al., 2005b; Molyneaux et al., 2005). *Fezf1* and *Fezf2* redundantly function to prevent the rostral forebrain from being the caudal diencephalon as the caudal diencephalon is expanded rostrally during early neural patterning in *Fezf1*- and *Fezf2*-deficient mice (Hirata et al., 2006a). In zebrafish, *fezf2* is required for the formation of dopaminergic (DA) neurons in the basal forebrain (Guo et al., 1999; Levkowitz et al., 2003; Rink and Guo, 2004).

Here, we have found that *Fezf1* and *Fezf2* directly repress the expression of *Hes5* and thereby derepress the expression of neurogenin 2 in the mouse neocortex. We show that the gene cascade *Fezf1/Fezf2* ⊣ *Hes5* ⊣ neurogenin 2 plays an important role in early differentiation of the neural stem cells into TUJ1$^+$ neurons or TBR2$^+$ intermediate progenitors, which are required for proper cortical development.

## MATERIALS AND METHODS

### Mouse mutants

Previous research has described the generation of mice that are *Fezf1*-deficient, mice that are *Fezf2*-deficient and mice that are both *Fezf1*-deficient and *Fezf2*-deficient (Hirata et al., 2006a; Hirata et al., 2006b; Hirata et al., 2004) [the respective accession numbers of *Fezf1*-deficient mice and *Fezf2*-deficient mice in the RIKEN Center for Developmental Biology (CDB) are CDB0497K and CDB0498K; http://www.cdb.riken.jp/arg/mutant%20mice%20list.html]. Both *Fezf1*$^{+/-}$ and *Fezf2*$^{+/-}$ were originally established in a 129SV genetic background and backcrossed to the C57BL/6 background for several generations. *Hes5*-deficient mice were described previously (Cau et al., 2000; Hatakeyama et al., 2004). For the current study, we housed mice in an environmentally controlled room at the Animal Facility of the RIKEN CDB under the institutional guidelines for animal and recombinant DNA experiments. The genotypes of newborn mice and embryos were determined by PCR analysis (Hirata et al., 2006b; Hirata et al., 2004). Noon of the day on which the vaginal plug was detected was designated as E0.5.

### Microarray analyses

The forebrain rostral to the caudal limit of the lateral ventricles was isolated manually from E9.5, E10.5 and E12.5 wild-type mice and from *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice. RNAs were isolated by Sepasol-RNA I (Nacalai Tesque) and were subjected to the One-Cycle Target Labeling procedure for biotin labeling by in vitro transcription (IVT; Affymetrix, Santa Clara, CA). The cRNA was subsequently fragmented and hybridized to the GeneChip Mouse Genome 430 2.0 Array (Affymetrix) according to the manufacturer's instructions. The microarray image data were processed with the GeneChip Scanner 3000 (Affymetrix) to generate CEL data. Data obtained from wild-type and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice were normalized according to the program's default setting. Two criteria were set for exploring the candidates for FEZF1 and FEZF2 downstream genes. First, the candidates were to have two-fold or more changes in signal value between wild-type and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ rostral forebrains. Second, the signal intensities of the higher value should be higher than 100. The microarray data have been deposited in Gene Expression Omnibus (GEO) under the accession number GSE21156.

### RNA probes and in situ hybridization

Mouse embryos were fixed with 4% paraformaldehyde (PFA) overnight at 4°C. Cryosections of the embryonic forebrain were prepared as described previously (Hirata et al., 2004). The samples were treated with 50 μg/ml Proteinase K for 8 minutes and then were post-fixed in 4% PFA for 15 minutes at room temperature. After the samples were washed with PBS, they were treated with 0.1 M triethanolamine-HCl (pH 8.0) followed by the addition of acetic anhydride. Hybridization and post-hybridization washing were performed as described previously (Shimizu et al., 2005). The samples were pre-incubated in the blocking solution (20% heat-inactivated goat serum in PBS, 0.1% Triton X-100) for 1 hour and incubated with 1/2000 diluted alkaline phosphatase (AP)- or peroxidase (HRP)-conjugated anti-digoxigenin antibodies (Roche Diagnostics Corp.) in the blocking solution at 4°C overnight. After undergoing three 30-minute washings with MABT (0.1 M maleic acid, 0.15 M NaCl and 0.1% Tween-20; pH 7.5), the samples underwent two 10-minute treatments with NTMT (0.1 M NaCl, 0.1 M Tris-HCl, 0.05 M $MgCl_2$ and 0.1% Tween-20; pH 9.5). NBT and BCIP (Roche) were used as the substrate for AP. Tyramid signal amplification (TSA) kits with Alexa Fluor 555 tyramide (Molecular Probes) were used to visualize the fluorescent signals. The probes were as follows: *Fezf1* (Hirata et al., 2006b), *Fezf2* (Hirata et al., 2004), *Hes5* (Ohtsuka et al., 1999), neurogenin 2 (Fode et al., 1998), *p73* (Meyer et al., 2004), reelin (D'Arcangelo et al., 1995) and *Rorb* (Nakagawa and O'Leary, 2003). The NBT and BCIP and fluorescent signals were obtained with AxioPlan2 imaging and an LSM5 Pascal laser-scanning inverted microscope (Zeiss), respectively. The fluorescent images were constructed from Z-stack sections by a 3D projection program associated with the microscope. Alexa Fluor 488 and 555 signals were colored green and magenta, respectively, for the figures.

### Immunohistochemistry

Cryosections of forebrains were blocked with 5% normal goat serum in PBS and then incubated with primary antibodies overnight at 4°C. After being rinsed with PBS, the sections were incubated with fluorescent secondary antibodies. The primary antibodies used in this study were anti-calretinin (1/400, Swant) (Schwaller et al., 1993), anti-NURR1 (NR4A2 – Mouse Genome Informatics; 1/100, R&D Systems) (Hoerder-Suabedissen et al., 2009), anti-PAX6 (1/200, Covance) (Marquardt et al., 2001), anti-TBR2 (1/500, Chemicon), anti-TBR1 (1/500, Abcam) (Englund et al., 2005), anti-CUX1 (1/100, Santa Cruz Biotech.), anti-TUJ1 (1/500, Sigma) (Lee et al., 1990), anti-chondroitin sulfate (1/200, Sigma) (Bicknese et al., 1994), anti-Ki67 (1/500, BD, Pharmingen), (Kubbutat et al., 1994), anti-neurogenin 2 (1/100, R&D Systems) (Lo et al., 2002), anti-BrdU (1/500, BD, Pharmingen) (Dolbeare et al., 1983) and anti-CTIP2 (1/500, Abcam) (Lai et al., 2008). The secondary antibodies were Alexa 488- or 555-conjugated goat anti-mouse, anti-rabbit or anti-rat IgG (Molecular Probes). For the anti-BrdU antibody, the Vectastain Elite ABC Kit (Vector) was also used for immunostaining with the HRP substrate diamino-benzidine (DAB). The DAB images were obtained with AxioPlan2 imaging.

### Chromatin immunoprecipitation assay

A chromatin immunoprecipitation (ChIP) assay was performed according to the protocol previously reported (Shimizu et al., 2008). Forebrains of E11.5 mouse embryos were mechanically dissociated and the cells were seeded on a poly-L-lysine-coated 24-well dish and cultured in DMEM containing 10% fetal calf serum overnight. The cells were fixed and used for ChIP assay. The PCR template was amplified with the following primers: 5′-GGATGCTAATGAGTGCGAGC-3′ and 5′-TGGAGCTCTGGAGGC-GATTAGC-3′. To raise monoclonal antibodies against FEZF1 and FEZF2, we generated glutathione S-transferase (GST) fusion protein containing amino acids (aa) 39-205 of FEZF1 or 134-266 of FEZF2 in *E. coli* BL21DE3. The GST fusion protein was purified by Glutathione Sepharose 4B (GE Healthcare) and used for immunization. Polyclonal antibodies against FEZF2 were generated by means of rabbit immunization with the synthetic peptide <u>C</u>TATPSAKDLARTVQS (the addition of the underlined C served to link the peptide covalently with keyhole limpet hemocyanin) as reported previously (Inoue et al., 2004). The control antibodies used for ChIP assays derived from pre-immune rabbit serum and control IgG (SantaCruz) for the polyclonal and monoclonal antibodies, respectively.

### BrdU incorporation assay

Pregnant females received a single intraperitoneal injection of BrdU (5′-bromo-2′deoxyuridine, 100 mg/kg). The pups were sacrificed 5 minutes after the injection or allowed to develop to the indicated period and then were fixed with 4% PFA.

### Luciferase reporter assay

Human embryonic kidney (HEK) 293 cells in a well of a 24-well plate were transfected with 0.1 μg of reporter plasmids pHes5-luc (Takebayashi et al., 1995), pHes1-luc (Nishimura et al., 1998) or 8xwtCBF1BS-luc

(Zhou et al., 2000), and an internal control plasmid, phRL (Promega), together with the expression plasmids pCS2+Fezf1, pCS2+Fezf2 and pME-FNIC, using a HilyMax transfection reagent (DOJINDO). On the following day, luciferase activity was measured with a Dual Luciferase Reporter Assay System (Promega). The full coding cDNA fragment of *Fezf1* and *Fezf2* was inserted into pCS2+ (Turner and Weintraub, 1994) in pCS2+Fezf1 and pCS2+Fezf2, respectively. The expression plasmid for the intracellular domain of mouse NOTCH1 (pME-FNIC) had been previously published (Nishimura et al., 1998).

### Immunoprecipitation and immunoblotting

HEK293 cells in a 6 cm dish were transfected with 5 μg of pCS2+Fezf1 or pCS2MT2+Fezf2 (contains six Myc tags). After 24 hours, the cells were lysed with 0.5 ml of a lysis buffer: 20 mM Tris-HCl pH 7.4, 150 mM NaCl, 1 mM EDTA, 1% NP40 and protease inhibitor cocktail (Nacalai). The lysates were immunoprecipitated with 10 μl of monoclonal antibodies (ascites) or 10 μl of polyclonal antibodies and blotted with anti-Myc (9E10, SantaCruz) or anti-FEZF1 antibodies. For direct detection (without immunoprecipitation), 10 μl of the lysates were used. The proteins were detected with HRP-conjugated goat anti-rabbit or anti-mouse IgG antibodies (TrueBlot, eBioscience) using a chemiluminescence system (Western Lightning; PerkinElmer Life Sciences).

### Statistics

Student's *t*-tests and ANOVA tests for comparisons involving two and more than two groups, respectively, were performed on the basis of GraphPad Prism 5.01 software.

## RESULTS

### Upregulation of *Hes5* and downregulation of neurogenin 2 in *Fezf1*- and *Fezf2*-deficient telencephalon

To investigate molecular mechanisms by which *Fezf1* and *Fezf2* control forebrain development, we searched downstream genes of *Fezf1* and *Fezf2* by microarray analyses. We isolated rostral forebrains, which contain the telencephalon and the rostral part of the diencephalon, from embryonic day (E) 9.5, E10.5 and E12.5 wild-type control and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ embryos and compared their expression profiles. We picked up genes whose expression is up- or downregulated more than two-fold in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ rostral forebrain (see Table S1 in the supplementary material). Many genes that are expressed in the caudal diencephalon (thalamus and pretectum) were upregulated in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ rostral forebrain at E12.5. They include *Tcf7l2*, *Dbx1*, *Ebf3*, *Brn3a* (*Pou4f1* – Mouse Genome Informatics) and *Irx1*/*2*/*3*/*5* (see Table S1 in the supplementary material). The data are consistent with our previous report that the caudal diencephalon is expanded in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Hirata et al., 2006a) and validate our strategy toward gene-expression profiling of the rostral forebrain.

The microarray data suggest that *Hes5* was upregulated at E9.5 and E10.5, and that the bHLH-type proneural gene neurogenin 2 was downregulated at E10.5 in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ rostral forebrain in comparison with the wild type. To confirm this, we carried out in situ hybridization. *Hes5* expression was indeed upregulated at both E9.5 and E10.5 in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 1D,H,L), but not in *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$ and *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ mice, in comparison with the control *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$ mice (Fig. 1A-C,E-G,I-K), suggesting that *Fezf1* and *Fezf2* function redundantly to repress *Hes5* expression in the rostral forebrain. We also confirmed downregulation of neurogenin 2 expression at E10.5 in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice in contrast to the control-mouse telencephalon (Fig. 1M,N). Simultaneous downregulation

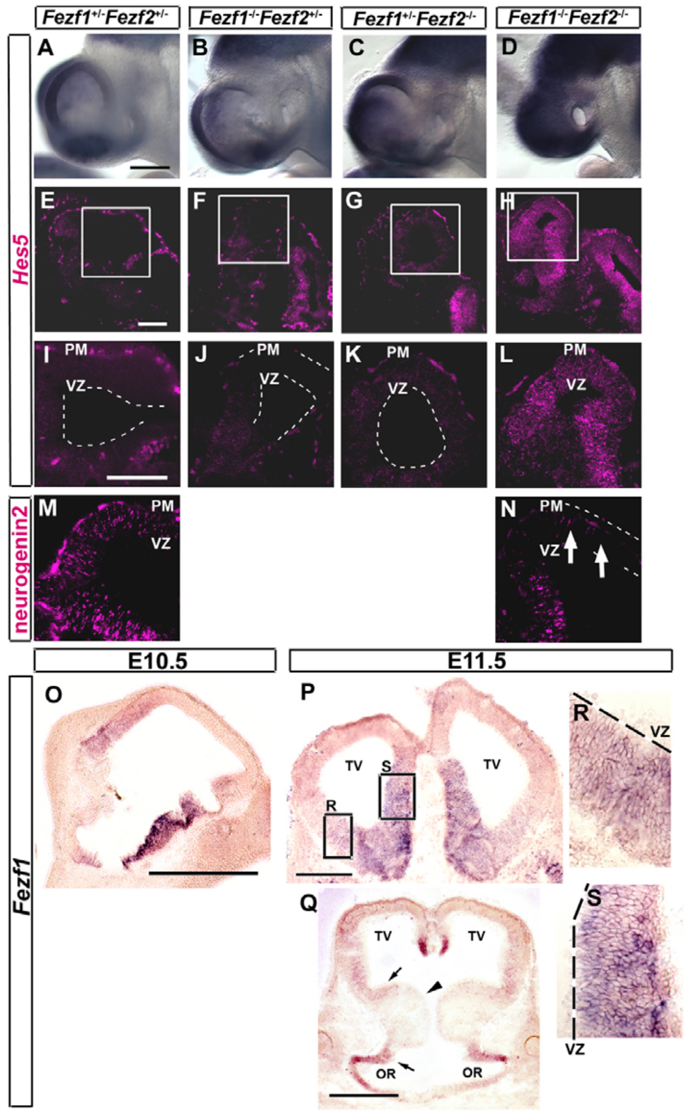


**Fig. 1. Upregulation of *Hes5* and downregulation of neurogenin 2 in the *Fezf1*- and *Fezf2*-deficient telencephalon.** (**A-L**) Using in situ hybridization, we analyzed expression of *Hes5* at E9.5 (A-D) or E10.5 (E-L) in the control (*Fezf1*$^{+/-}$*Fezf2*$^{+/-}$; A,E,I), *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$ (B,F,J), *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ (C,G,K) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (D,H,L) mouse embryos. Wholemount (A-D) and sagittal sections (E-L) with rostral to the left. I-L are higher magnification views of the boxes in E-H. *Hes5* expression in telencephalon was upregulated in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ embryos at both E9.5 ($n$=2) and E10.5 ($n$=3) in comparison with the control embryos. *Hes5* expression in telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$ and *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ embryos was comparable with that of the control embryos. (**M**,**N**) Expression of neurogenin 2 at E10.5 in control *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$ (M) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (N) embryos. neurogenin 2 expression was downregulated in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon in comparison with the control telencephalon (arrows, $n$=3). (**O-S**) Expression of *Fezf1* in telencephalon at E10.5 (O) and E11.5 (P-S). Sagittal section with rostral to the left (O); transverse sections of telencephalons at the rostral (P) and medial (Q) levels. R and S are higher-magnification views of the boxes in P. *Fezf1* was detected in the VZ of the dorsal telencephalon and pre-optic regions (arrows) but not in the ventral telencephalon (arrowhead). OR, optic recess; PM, pia mater; TV, telencephalic vesicle; VZ, ventricular zone. Scale bars: 200 μm in A,E,I,P; 500 μm in O,Q. Magnifications of A and B-D; E and F-H; I and J-N; and R and S are the same.

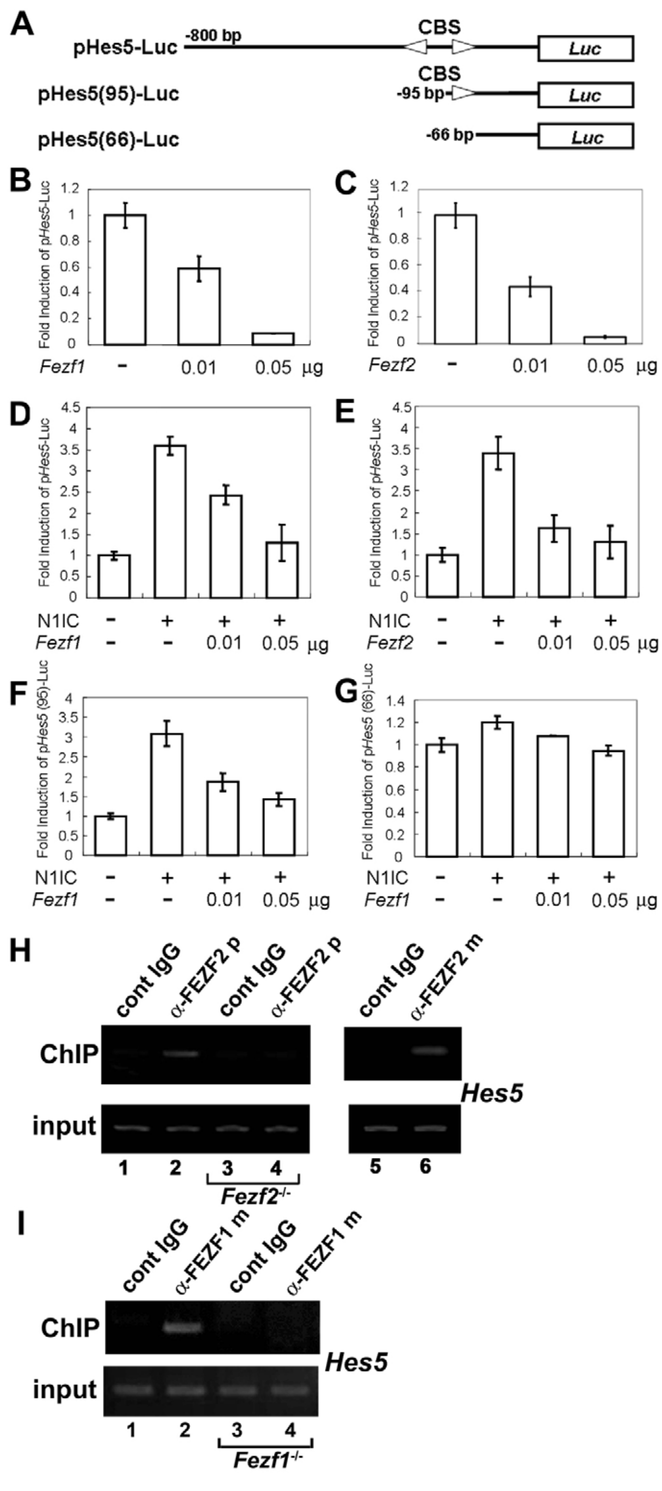


**Fig. 2. FEZF1 and FEZF2 repress *Hes5* promoter activity.** (**A**) Schematic drawing of *Hes5* promoter-luciferase constructs. CBS, CBF1 (RBPjκ)-binding site; Luc, luciferase. Number of nucleotides from the transcription initiation site is indicated. (B-G) Luciferase reporter assays in HEK293 cells. (**B-E**) Overexpression of *Fezf1* or *Fezf2* represses both the basal activity of *Hes5* 800 bp promoter (B,C; $P<0.001$, ANOVA test) and Notch-mediated *Hes5* 800 bp promoter activation (D,E; $P<0.001$). (**F**,**G**) Overexpression of *Fezf1* represses Notch-mediated *Hes5* 95 bp promoter activation (F; $P<0.001$) but does not repress Notch-mediated *Hes5* 66 bp promoter activation. N1IC, intracellular domain of NOTCH1 (G). The amount of *Fezf1* or *Fezf2* expression plasmids used for transfection is indicated; 0.05 µg of N1IC expression plasmid was transfected (+; D-G). Data are represented as mean +/– standard deviation. (**H**) FEZF2 binds to the *Hes5* promoter in vivo. Chromatin was prepared from E11.5 wild-type (lanes 1, 2, 5, 6) or *Fezf2*$^{-/-}$ (lanes 3, 4) forebrain cells after an overnight culture and was immunoprecipitated with polyclonal (lanes 1-4) or monoclonal (lanes 5, 6) anti-FEZF2 antibodies, or control antibodies (lanes 1, 3, 5). The *Hes5* promoter fragment was amplified from the immunoprecipitates (ChIP, upper) and the input lysates (lower) by PCR. (**I**) FEZF1 binds to the *Hes5* promoter in vivo. Chromatin was prepared from E11.5 wild-type (lanes 1, 2) or *Fezf1*$^{-/-}$ forebrains (lanes 3, 4) and was immunoprecipitated with monoclonal anti-FEZF1 (lanes 2, 4) or control antibodies (lanes 1, 3).

of neurogenin 2 and upregulation of *Hes5* is consistent with the notion that neurogenin 2 is negatively regulated by Hes-family genes (Kageyama et al., 2005; Ross et al., 2003).

The redundant function of *Fezf1* and *Fezf2* suggests that they are co-expressed in the early dorsal telencephalon. *Fezf2* was reported to be expressed in the VZ of the dorsal telencephalon as early as E10.5 (Chen et al., 2005b). We found that *Fezf1* was also expressed in the VZ of the dorsal telencephalon at E10.5 and E11.5 (Fig. 1O-S). All of these data suggest that, during early neurogenesis in the dorsal telencephalon, both *Fezf1* and *Fezf2* are expressed in the VZ and might function to repress *Hes5* expression and thereby derepress neurogenin 2 expression.

## FEZF1 and FEZF2 directly repress *Hes5* promoter activity

Both FEZF1 and FEZF2 contain an EH1 repressor motif (Hashimoto et al., 2000; Hirata et al., 2006b) and zebrafish Fezf2 is shown to function as a transcriptional repressor in some context (Levkowitz et al., 2003). These findings suggest that FEZF1 and FEZF2 directly repress the promoter activity of *Hes5*. To address this issue, we examined the effect of *Fezf1* or *Fezf2* expression on *Hes5* promoter activity by a luciferase reporter assay in non-neural human embryonic kidney (HEK) 293 cells (Fig. 2A). Basal *Hes5* promoter activity in HEK293 cells was reduced by expression of either *Fezf1* or *Fezf2* (Fig. 2B,C). When an expression vector of the intracellular domain of NOTCH1 (N1IC: a constitutively active form of NOTCH1) was introduced, the *Hes5* promoter was activated as previously reported (Nishimura et al., 1998) (Fig. 2D,E). Expression of *Fezf1* or *Fezf2* suppressed the NOTCH1-dependent *Hes5* promoter activity (Fig. 2D,E).

We further investigated a *Hes5* promoter region responsible for *Fezf1*- or *Fezf2*-mediated repression with luciferase reporters containing a 5′ truncated promoter. The 95 bp promoter reporter [pHes5(95)-luc; Fig. 2A], which contains a CBF1(RBPjκ)-binding site (CBS), responded to expression of N1IC, and the basal and NOTCH1-mediated promoter activity was repressed by *Fezf1* or *Fezf2* (Fig. 2F; data not shown for *Fezf2*; see also Fig. S1 in the supplementary material). By contrast, the 66 bp promoter reporter [pHes5(66)], which lacks the CBS site, neither responded to N1IC expression nor was repressed by *Fezf1* or *Fezf2* (Fig. 2G; data not shown for *Fezf2*). The data suggest that a region responsible for *Fezf1*- or *Fezf2*-mediated repression is located between –99 and 65 bp in the *Hes5* promoter. This region contains a CBS, suggesting that FEZF1 and FEZF2 repress the *Hes5* promoter by inhibiting a Notch signaling pathway. However, *Fezf1* or *Fezf2* could suppress

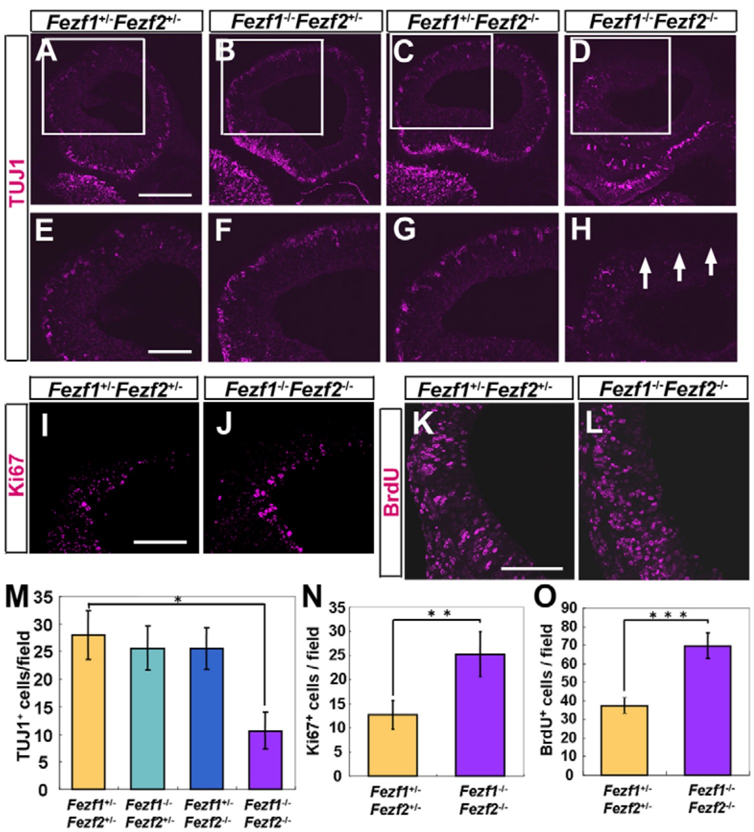

**Fig. 3. Reduced neurogenesis and increased proliferation in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon.** (**A-H**) Immunostaining with the anti-neuron-specific βIII tubulin antibody (TUJ1) of E10.5 control (*Fezf1*$^{+/-}$*Fezf2*$^{+/-}$; A,E), *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$ (B,F), *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ (C,G) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (D,H) forebrains. Sagittal sections with rostral to the left. E-H are higher-magnification views of the boxes in A-D. Note that TUJ1$^{+}$ neurons were reduced in caudal telencephalon (arrows in H, *n*=5). (**I**,**J**) Immunostaining with the anti-Ki67 antibody of the E10.5 control (I) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (J) forebrain. Note that Ki67$^{+}$ proliferating cells were increased in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon (*n*=4). (**K**,**L**) BrdU incorporation at E10.5. Control (*Fezf1*$^{+/-}$*Fezf2*$^{+/-}$; K) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (L) embryos were labeled with bromodeoxyuridine (BrdU) for 5 minutes and proliferating cells were analyzed by immunostaining with anti-BrdU antibody. (**M-O**) Number of TUJ1$^{+}$ (M, *n*=5), Ki67$^{+}$ (N, *n*=4) or BrdU$^{+}$ (O, *n*=3) telencephalic cells in a comparable sagittal section for each genotype was counted. Data are represented as mean ± standard deviation. TUJ1$^{+}$ cells were reduced (*, *P*<0.01, Student's *t*-test), Ki67$^{+}$ cells were increased (**, *P*<0.01) and BrdU$^{+}$ cells were increased (***, *P*<0.01) in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon in contrast to the control. Scale bars: 200 μm in A; 100 μm in E,I,K,. Magnifications of A and B-D; E and F-H; I and J; and K and L are the same.

the *Hes5* promoter in the absence of Notch signaling (Fig. 2B,C) but did not suppress basal or NOTCH1-mediated promoter activity of *Hes1*, which is another downstream target of Notch signaling (Nishimura et al., 1998; Ohtsuka et al., 1999), or Notch-mediated activation of an artificial promoter containing multiple CBSs (see Fig. S2 in the supplementary material). These findings indicate that FEZF1 and FEZF2, rather than inhibit Notch cytoplasmic signaling, specifically repress the *Hes5* promoter.

To address whether FEZF1 and FEZF2 bind to the *Hes5* promoter in vivo, we carried out a chromatin immunoprecipitation (ChIP) assay with anti-FEZF1 and anti-FEZF2 antibodies (Fig. 2H,I; see Fig. S3 in the supplementary material). Although anti-FEZF1 and anti-FEZF2 antibodies did not precipitate the *Hes5* promoter from E11.5 *Fezf1*$^{-/-}$ and *Fezf2*$^{-/-}$ forebrain cells, respectively, both of the antibodies could precipitate the *Hes5* promoter from wild-type forebrain cells (Fig. 2H,I). These data reveal that FEZF1 and FEZF2 bind to and directly repress the *Hes5* promoter in vivo.

### *Fezf1* and *Fezf2* control neurogenesis during early corticogenesis

Hes-family and neurogenin-family bHLH genes are negative and positive regulators of neurogenesis (Kageyama et al., 2005; Kageyama et al., 2007; Kageyama et al., 2008a; Ross et al., 2003). Thus, we assumed that upregulation of *Hes5* and downregulation of neurogenin 2 in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice might lead to abnormal neurogenesis and might explain cortical developmental defects observed in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Hirata et al., 2006a). To address this issue, we performed immunostaining with anti-TUJ1 and anti-Ki67 antibodies, which are markers for differentiated neurons and proliferating progenitor cells (Fig. 3). TUJ1$^{+}$ neurons were comparable in the telencephalon of *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$, *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$ and *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ mice at E10.5 (Fig. 3A-C,E-G,M), whereas TUJ1$^{+}$ neurons were strongly reduced in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 3D,H,M). By contrast, Ki67$^{+}$ proliferating neural progenitors were slightly increased in the telencephalic VZ of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice in comparison with the corresponding progenitors of *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$ mice (Fig. 3I,J,N). Furthermore, we found that *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons had more proliferating cells that incorporated BrdU at E10.5 than the control telencephalons (Fig. 3K,L,O). These results indicate that neuronal differentiation was suppressed and that the neural stem cells continued to proliferate during early corticogenesis in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice. These findings are consistent with the upregulation of *Hes5* and the downregulation of neurogenin 2 observed in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon and with the notion that *Hes5* suppresses neurogenesis and that neurogenin 2 promotes neuronal differentiation. These findings suggest that *Fezf1* and *Fezf2* control neurogenesis through the *Hes5*-neurogenin 2 gene cascade in the dorsal telencephalon.

### *Fezf1* and *Fezf2* control generation of early-born telencephalic neurons

The earliest born neurons in the dorsal telencephalon appear around E10.5-E11.5 in mice and form the pre-plate, which is later split into the more superficial marginal zone (MZ) and the deeply located subplate (SP) (Aboitiz et al., 2005; Molyneaux et al., 2007). The marginal zone (layer I) contains Cajal-Retzius (CR) cells, which are derived from three regions: the caudomedial cortical hem (Meyer et al., 2002; Takiguchi-Hayashi et al., 2004; Yoshida et al., 2006), the pallial-subpallial boundary and the septum (Bielle et al., 2005). As neurogenesis was impaired in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon at E10.5, the formation of early-born telencephalic neurons might be affected in these mice. With this in mind, we examined expression of markers of the SP neurons and CR cells. Chondroitin sulfate proteoglycan (CSPG) normally accumulated in the pre-plate and was later concentrated in the SP region (Sheppard et al., 1991; Sheppard and Pearlman, 1997) (E16.5; Fig. 4A), and NURR1 was also a specific marker for the SP neurons (Arimatsu et al., 2003; Hoerder-Suabedissen et al., 2009) (Fig. 4C). In *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon, the CSPG and NURR1 signals were strongly reduced (Fig. 4B,D). Furthermore, cells that had incorporated BrdU at E11.5 were located in the SP region in the control at E16.5 (Sheppard and Pearlman, 1997) (Fig. 4K) but were strongly reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 4L). We previously reported that differentiation of the SP neurons was affected in *Fezf2*-deficient mice (Hirata et al., 2004; Molyneaux et al., 2005). By contrast, our data from the present study indicate that *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice had defects in generation of the SP neuron.

CR cells were stained with the anti-calretinin antibody at E11.5 (del Rio et al., 1995) or a reelin probe at post-natal day 0 (P0) in the control mice (Alcantara et al., 1998) (Fig. 4E,G), but calretinin$^{+}$ or reelin$^{+}$ CR cells were strongly reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 4F,H). An early marker for CR neurons derived from the cortical hem is *p73* (Meyer et al., 2004; Meyer et al., 2002), which was detected in the MZ of the control mice at E13.5 (Fig. 4I). *p73*-positive CR cells were strongly reduced in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 4J). These findings indicate that *Fezf1* and *Fezf2* are involved in the generation of the early-born cortical neurons.

We further examined cortical-layer markers (Fig. 5). There were no significant differences in numbers of TBR1$^{+}$ layer-VI neurons between *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$ and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 5D; *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$, 98±6.98 and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$, 99±9.68 cells/field). CTIP2$^{+}$ layer-V neurons were absent in both *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 5C). This phenotype was reported for *Fezf2*-deficient mice (Chen et al., 2005a; Molyneaux et al., 2005). In addition, *Rorb*-positive layer-IV neurons were reduced in the rostral part of the cortex of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$, but not of *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$, mice (Fig. 5B). CUX1$^{+}$ layer II-IV neurons and SATB2$^{+}$ corticocortical neurons (Alcamo et al., 2008; Britanova et al., 2008) were not significantly affected in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (Fig. 5A; data not shown for SATB2). Therefore, *Fezf1* and *Fezf2* redundantly function to generate the early-born neurons and the layer-IV neurons, but not the late-born neurons (see Fig. S4 in the supplementary material).

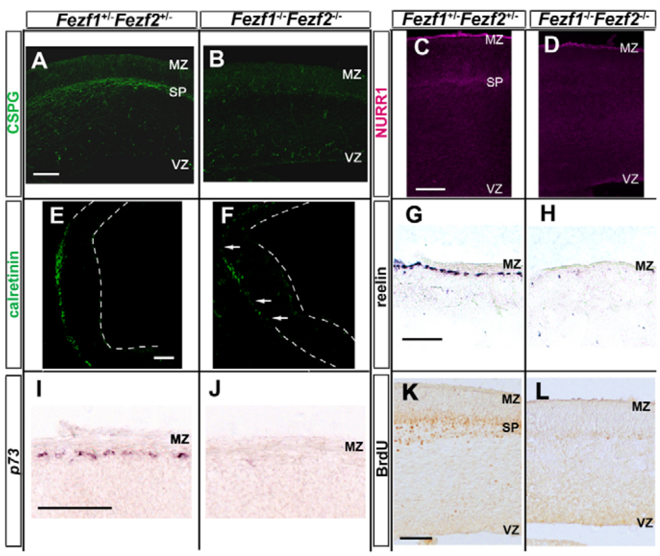


**Fig. 4. Reduction of early-born cortical neurons in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons.** (**A**,**B**) Immunostaining with the anti-chondroitin sulfate proteoglycan (CSPG) antibody of E16.5 control (A; *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (B) telencephalons. Coronal sections. CSPG signals were reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons ($n$=3). (**C**,**D**) Immunostaining with the anti-NURR1 antibody of E16.5 control (C) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (D) telencephalons. (**E**,**F**) Immunostaining with the anti-calretinin antibody of E11.5 control (E) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (F) telencephalons. Coronal sections. calretinin$^{+}$ Cajal-Retzius cells were reduced in the lateral telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ embryos (arrows in F, $n$=3). (**G**,**H**) In situ hybridization with the reelin probe of P0 control (G) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (H) telencephalons. reelin-expressing Cajal-Retzius cells were reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons ($n$=2). (**I**,**J**) In situ hybridization with the *p73* probe of E13.5 control (I) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ (J) telencephalons. *p73*-positive Cajal-Retzius cells in the marginal zone were decreased in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ embryos ($n$=2). (**K**,**L**) Birthdate analysis. BrdU was injected at E11.5. The forebrain was fixed at E16.5 and stained with the anti-BrdU antibody. Coronal sections. BrdU$^{+}$ cells were reduced in the subplate of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ embryos (L, $n$=3). MZ, marginal zone; SP, subplate; VZ, ventricular zone. Scale bars: 100 μm in A,C,E; 500 μm in G; 200 μm in I,K.

## Defects in the formation of intermediate progenitors in *Fezf1*- and *Fezf2*-deficient telencephalon

Cortical neurons are differentiated from the neural stem cells in the VZ, and are also generated from TBR2$^{+}$ intermediate progenitors that are derived from the neural stem cells in the VZ (Arnold et al., 2008; Kowalczyk et al., 2009; Sessa et al., 2008). Notch signaling has been shown to be involved in the generation of the intermediate progenitors (Mizutani et al., 2007; Yoon et al., 2008). In an attempt to reveal the role of *Fezf1* and *Fezf2* in the formation of the intermediate progenitors, we analyzed the neural stem cells and the intermediate progenitors in the mutant telencephalon by immunostaining with anti-PAX6 and anti-TBR2 antibodies (Englund et al., 2005; Gotz et al., 1998). PAX6$^{+}$ neural stem cells were not strongly reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice from E11.5 through E13.5 (Fig. 5E-J). By contrast, the TBR2$^{+}$ intermediate progenitors were decreased in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice in comparison with the control mice at these stages (Fig. 5K-R). These data suggest that differentiation of the neural stem cells into the intermediate progenitors was impaired in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ dorsal telencephalon.

## Loss of the *Hes5* gene suppresses defects in neurogenesis in *Fezf1*- and *Fezf2*-deficient telencephalon

In light of the above observations, the neurogenesis defects observed in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ cortex might stem from upregulation of *Hes5* expression. To genetically prove this hypothesis, we carried out an epistatic analysis by crossing *Fezf1*- and *Fezf2*-deficient mice and *Hes5*-deficient mice. TUJ1$^{+}$ neurons and neurogenin 2$^{+}$ intermediate progenitors and neurons were not affected in the *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$*Hes5*$^{-/-}$ telencephalon at E10.5 (Fig. 3A; Fig. 6A,D,G). This is consistent with the previous report that *Hes5* deficiency induces upregulation of *Hes1*, which compensates for loss of *Hes5* (Hatakeyama et al., 2004). TUJ1$^{+}$ or neurogenin 2$^{+}$ cells were reduced in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ telencephalon (Fig. 6B,E,H), whereas they were recovered in the

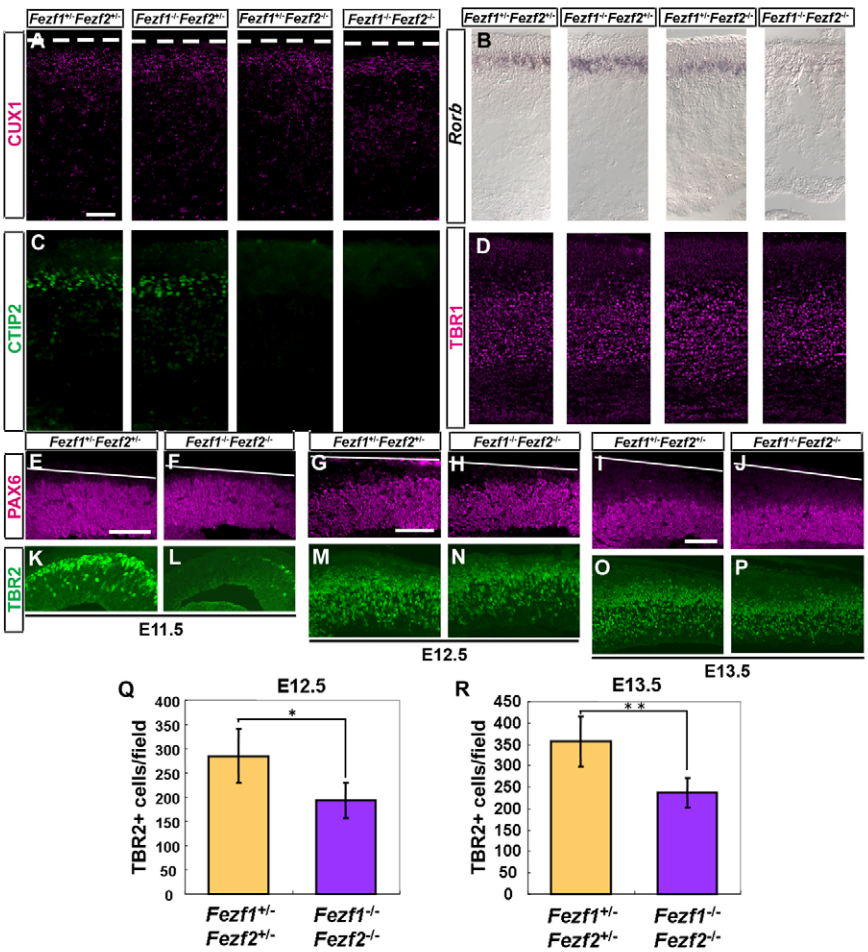


**Fig. 5. *Fezf1* and *Fezf2* control the generation of intermediate progenitors in telencephalons.** (**A-D**) Cortical layer formation in P0 control (*Fezf1*$^{+/-}$*Fezf2*$^{+/-}$), *Fezf1*$^{-/-}$*Fezf2*$^{+/-}$, *Fezf1*$^{+/-}$*Fezf2*$^{-/-}$ and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons. Immunostaining with anti-CUX1 (A; marker for layers II, III and IV, *n*=2), anti-CTIP2 (C; layer V, *n*=2) or anti-TBR1 (D; layer VI, *n*=2) antibodies; in situ hybridization with the *Rorb* probe (B; layer IV, *n*=4). Coronal sections. (**E-P**) Apical and intermediate progenitors. Immunostaining with anti-PAX6 (E-J; marker for neural stem cells) or anti-TBR2 (K-P; marker for intermediate progenitors) antibodies of E11.5 (E,F,K,L; *n*=2), E12.5 (G,H,M,N; *n*=4), and E13.5 (I,J,O,P; *n*=3) control and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons. Coronal sections. MZ, marginal zone; SP, subplate; VZ, ventricular zone. (**Q**,**R**) Numbers of TBR2$^{+}$ cells in control and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons at E12.5 (Q) and E13.5 (R). TBR2$^{+}$ cells in a comparable coronal section were counted for each genotype. Data are represented as mean ± standard deviation. TBR2$^{+}$ cells were reduced in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons in comparison with the control at E12.5 (*, $P<0.01$, Student's *t*-test) and E13.5 (**, $P<0.05$). Scale bars: 100 μm in A,E,G,I. Magnifications of A and B-D; E and F,K,L; G and H,M N; and I and J,O,P are the same.

*Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ telencephalon (Fig. 6C,F,I,J). These data indicate that the *Hes5* deficiency suppressed neurogenesis defects in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon.

We then sought to analyze the phenotypes of the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ forebrains in more depth. As reported previously (Hirata et al., 2006a), *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice showed defects in rostro-caudal polarity of the forebrain: loss of olfactory bulbs and prethalamus, and reduction in thalamus (Fig. 7A,B). These defects were not recovered in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ mice (Fig. 7C). The generation of CTIP2$^{+}$ layer-V neurons was also not recovered in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ forebrains (Fig. 7J-L). However, the generation of calretinin$^{+}$ CR cells, CSPG-expressing subplate neurons, *Rorb*-positive layer-IV neurons and TBR2$^{+}$ intermediate progenitors were recovered in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ telencephalons in comparison with the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ telencephalons (Fig. 7D-R). These data suggest that *Fezf1* and *Fezf2* control rostro-caudal polarity of forebrain and specification of layer-V neurons in a *Hes5*-independent manner. By contrast, *Fezf1* and *Fezf2* control the generation of early-born cortical neurons and intermediate progenitors by repressing *Hes5* expression.

## DISCUSSION

### Role of *Fezf1* and *Fezf2* in differentiation of neural stem cells

An important question about neural development is how the differentiation of neural stem cells is precisely controlled in the forebrain. Asymmetric cell division of neural stem cells is thought to contribute to the differentiation of neural stem cells (radial glial cells) into either neurons or intermediate progenitors (Gotz and Huttner, 2005). Recent reports suggest that the orientation of stem cell division in the VZ might not directly control which of the two asymmetrically divided cells becomes a stem cell and which of the two becomes a differentiated cell (Konno et al., 2008; Morin et al., 2007). Although asymmetric centrosome inheritance during the asymmetric cell divisions was reported to play a role in the maintenance of the neural stem cells (Wang et al., 2009), it is not clear what factors determine cell fate. It is known that oscillation of *Hes1* and neurogenin 2 expression in the telencephalic VZ plays an important role in maintenance of the neural stem cells and that stabilization of neurogenin 2 expression supports differentiation of the neural stem cells (Kageyama et al., 2008b; Shimojo et al., 2008). However, it is still not understood what factor(s) control stabilization of neurogenin 2 expression and what factor(s) induce their differentiation. These reports imply that, besides asymmetric distribution of cell-fate determinants, extrinsic and intrinsic factors might bias the neural stem cells toward differentiation. Notch signaling plays an essential role in maintenance of the neural stem cells (Gaiano and Fishell, 2002; Louvi and Artavanis-Tsakonas, 2006; Yoon and Gaiano, 2005). Thus, regulators of Notch signaling and its downstream effectors might be involved in the decision as to whether to be a stem cell or a differentiated cell. In this report, we demonstrate that *Fezf1* and *Fezf2*, which are expressed in the neural stem cells at the beginning of mouse cortical development (Chen et al., 2005b; Hirata et al., 2006b; Hirata et al., 2004) (Fig. 1O-S), inhibit the expression of the Notch effector *Hes5* and

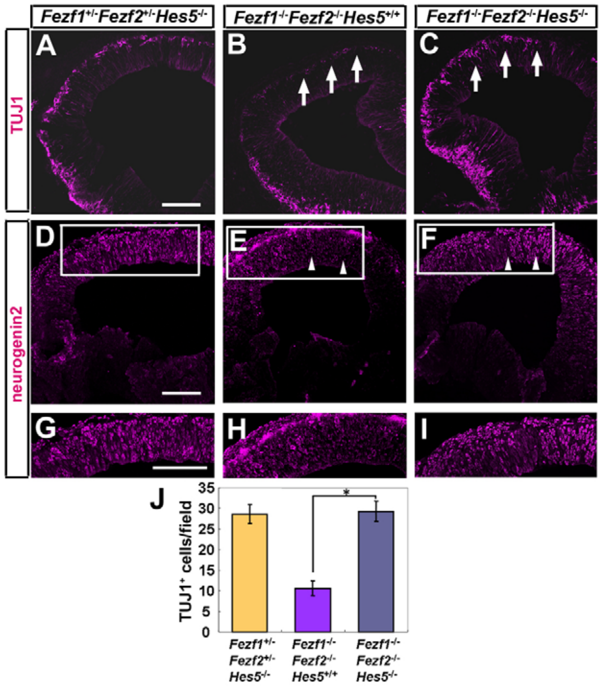


**Fig. 6. Loss of *Hes5* suppresses neurogenesis defects in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons.** (**A-I**) Immunostaining with anti-TUJ1 (A-C) and anti-neurogenin 2 antibodies (D-I) of E10.5 *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$*Hes5*$^{-/-}$ (A,D,G), *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ (B,E,H) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ (C,F,I) telencephalons. Sagittal sections with rostral to the left. G-I are higher-magnification views of the boxes in D-F. TUJ1$^{+}$ neurons (arrows) and neurogenin 2$^{+}$ cells (arrowheads) in the telencephalons were increased in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ embryos (C,F) in comparison with *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ embryos (B,E). (**J**) Number of TUJ1$^{+}$ telencephalic cells. TUJ1$^{+}$ cells in a comparable sagittal section were counted for each genotype. Data are represented as mean ± standard deviation. *, $P$<0.001 ($n$=3, Student's $t$-test). Scale bars: 100 μm.

promote differentiation of the neural stem cells. Our findings suggest that *Fezf1* and *Fezf2* function as intrinsic factors to bias the neural stem cells toward differentiation.

Expression of *fezf2* takes place in the radial glial cells of the telencephalic VZ of adult zebrafish (Berberoglu et al., 2009). *fezf2* is also expressed in the neural progenitors and neurons in the pre-optic region and hypothalamus of the adult zebrafish brains (Berberoglu et al., 2009). In zebrafish, neurogenesis continuously takes place in adult brains (Adolf et al., 2006; Grandel et al., 2006; Zupanc et al., 2005). It is possible that *fezf2* might control differentiation of the neural stem cells in the adult zebrafish forebrain as *Fezf1* and *Fezf2* do during early mouse cortical development.

## FEZF1 and FEZF2 directly repress the *Hes5* promoter

Expression of *Fezf1* or *Fezf2* repressed both NOTCH1-dependent and NOTCH1-independent *Hes5* promoter activity, but did not repress the *Hes1* promoter or the artificial CBS-dependent promoter (Fig. 2; see Fig. S1 and S2 in the supplementary material). *Hes1* expression was not upregulated in the telencephalon of *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mice (data not shown). Furthermore, FEZF1 and FEZF2 bound to the *Hes5* promoter in vivo in the mouse forebrain (Fig. 2). All of these data indicate that FEZF1 and FEZF2, rather than inhibit Notch cytoplasmic signaling, specifically bind to and directly repress the *Hes5* promoter. FEZF1 and FEZF2 have an EH1 repressor motif (Hashimoto et al., 2000; Hirata et al., 2006b; Shimizu and Hibi, 2009). Our data support the assertion that FEZF1 and FEZF2 function as transcriptional repressors and repress the *Hes5* promoter at least during early cortical development. *Hes5* deficiency suppressed neurogenesis defects in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon (Figs 6, 7), supporting the hypothesis that *Fezf1* and *Fezf2* suppress the expression of *Hes5* and thereby control differentiation of the neural stem cells.

FEZF1 and FEZF2 repress only *Hes5*. *Hes1* and *Hes5* function redundantly in the maintenance of neural stem cells in the mouse central nervous system (Hatakeyama et al., 2004), whereas only *Hes1* is reported to exhibit oscillatory expression in the neural stem cells (Shimojo et al., 2008), suggesting that *Hes1* and *Hes5* might have distinct roles in neurogenesis. Previous research has revealed that oscillation of *Hes1* is involved in the maintenance of neural stem cells (Kageyama et al., 2008b; Shimojo et al., 2008) and, in the current study, we speculate that *Hes5* plays a different role in neurogenesis; specifically, we propose that *Hes5*, in contrast to *Hes1*, sets up the overall expression levels of *Hes* genes and neurogenin 2 in the forebrain. Once *Fezf1* and *Fezf2* expression exceeds a threshold, FEZF1 and FEZF2 might repress *Hes5* expression, stabilize neurogenin 2 expression and thereby bias the neural stem cells toward differentiation.

It has recently been reported that the *Drosophila* homolog of *Fezf1/2* (*dFezf* or *Earmuff*) restricts the developmental potential of intermediate progenitors by negatively regulating Notch signaling (Weng et al., 2010). Although the mechanism by which *dFezf* represses Notch signaling is unknown, *Fezf* family genes function to negatively regulate Notch signaling in both vertebrates and invertebrates.

## *Fezf1*- and *Fezf2*-mediated cortical development

*Fezf1* and *Fezf2* function to repress the caudal diencephalon fate and their function is involved in proper rostro-caudal patterning of the forebrain (Hirata et al., 2006a; Jeong et al., 2007). The prospective telencephalon domain is already smaller in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ mouse embryos than in the wild type at E9.5, before neurogenesis is initiated in the telencephalon (Hirata et al., 2006a) (Fig. 1A,D). Therefore, the defect in rostro-caudal patterning is attributable to reduction of the telencephalon domain. In addition, *Fezf2*$^{-/-}$ or *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon lacks layer-V subcerebral projection neurons (Chen et al., 2005a; Molyneaux et al., 2005) (Fig. 5). *Hes5* deficiency did not suppress the defects in rostro-caudal patterning of the forebrain or specification of layer-V neurons in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ forebrains (Fig. 7). Therefore, *Fezf1/2*-mediated downregulation of *Hes5* is not involved in the rostro-caudal patterning of the forebrain and the specification of layer-V neurons (Fig. 7S). *Fezf1* and/or *Fezf2* probably control genes other than *Hes5* to elicit these functions.

*Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon exhibited reduced formation of early-born neurons such as SP neurons and CR cells (Fig. 4). A birthdate analysis revealed that the reduction of SP neurons and CR cells was not due to mis-specification of these neurons to other types of neurons (Fig. 4). Our data suggest that generation of the neural stem cells into SP neurons and CR cells is impaired in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon. This finding is consistent with a reduction of differentiated (TUJ1$^{+}$) neurons in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon at E10.5 (Fig. 3), when SP neurons and CR cells were born in the VZ. *Hes5* deficiency rescued neurogenin 2

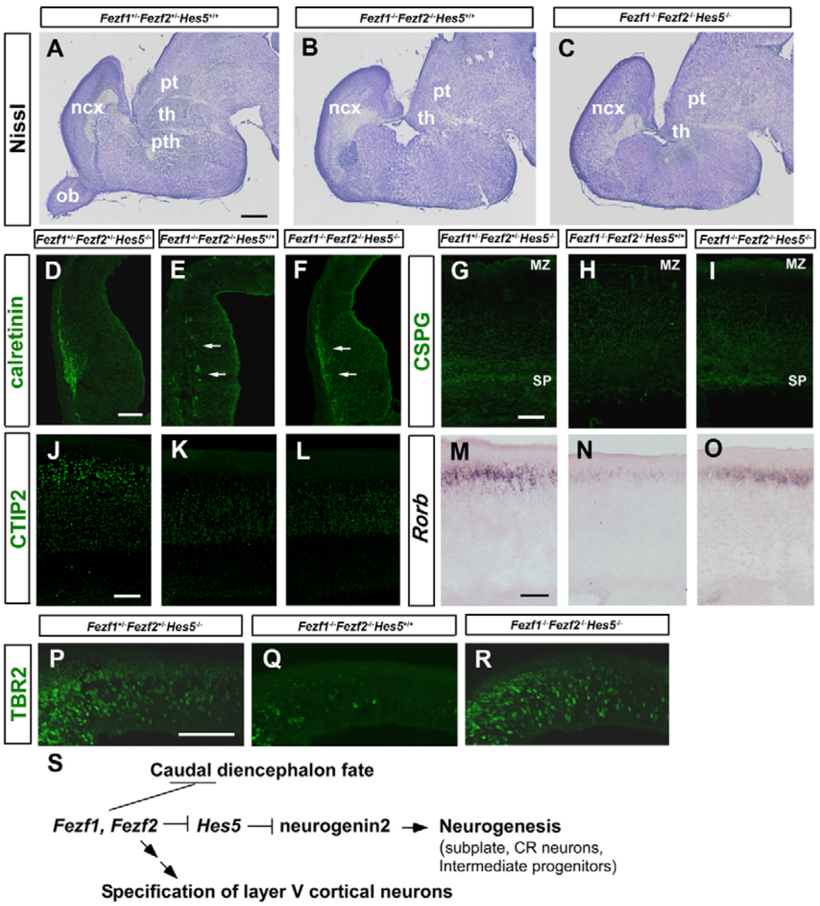


**Fig. 7. *Hes5* deficiency rescues the generation of early-born cortical neurons and intermediate progenitors in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalons.** (**A-C**) Nissl staining. Sagittal sections of P0 *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$*Hes5*$^{+/+}$ (A), *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ (B) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ (C) brains. Loss of olfactory bulb and prethalamus, and reduction of thalamus observed in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ forebrains was not recovered in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ forebrains. ncx, neocortex; ob, olfactory bulb; pt, pretectum; pth, prethalamus; th, thalamus. (**D-O**) Immunostaining with anti-calretinin (D-F), anti-CSPG (G-I) and anti-CTIP2 (J-L) antibodies; in situ hybridization with *Rorb* (M-O) of *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$*Hes5*$^{-/-}$ (D,G,J,M), *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ (E,H,K,N) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ (F,I,L,O) telencephalons. Coronal sections. E11.5 (D-F) and P0 (G-O). MZ, marginal zone; SP, subplate. Signals for calretinin (Cajal-Retzius cells), CSPG (subplate neurons) and *Rorb* (layer-IV neurons) were reduced or absent in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ telencephalons but were rescued in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ telencephalons (*n*=2). CTIP2$^{+}$ layer-V neurons were not recovered in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ telencephalons (*n*=2). (**P-R**) Immunostaining with the anti-TBR2 antibody of E11.5 *Fezf1*$^{+/-}$*Fezf2*$^{+/-}$*Hes5*$^{-/-}$ (P), *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{+/+}$ (Q) and *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ (R) telencephalons. Coronal sections. TBR2$^{+}$ intermediate progenitors were restored in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$*Hes5*$^{-/-}$ telencephalons (*n*=2). (**S**) Schematic diagram of the roles for *Fezf1* and *Fezf2* in forebrain development. Scale bars: 500 μm in A; 100 μm in D,G,J,M,P. Magnifications of A and B,C; D and E,F; G and H,I; J and K,L; M and N,O; P and Q,R are the same.

expression at E10.5 and the generation of SP neurons and CR cells (Figs 6, 7) in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon, indicating that *Fezf1*- and/or *Fezf2*-mediated repression of *Hes5* plays an important role in the generation of these early-born cortical neurons (Fig. 7S). It is reported that formation of CR cells in the choroid plexus region, near the cortical hem, is controlled by a *Hes*-neurogenin cascade but that the Notch signal-mediated lateral inhibition is not involved in regulation of the *Hes*-neurogenin cascade in the CR cell development (Imayoshi et al., 2008). *Fezf1* and *Fezf2* are expressed in the dorsomedial telencephalon (Hirata et al., 2006b; Hirata et al., 2004). Our data suggest that *Fezf1* and *Fezf2* might control the development of CR cells by regulating *Hes5* and neurogenin 2 expression in the choroid plexus domain.

*Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon had normal upper-layer (layer II, III) neurons but displayed a reduction of layer-IV neurons (Fig. 5). There are two plausible explanations for this finding: *Fezf1* and *Fezf2* regulate the specification of layer-IV neurons or *Fezf1* and *Fezf2* control the generation of layer-IV neurons (Chen et al., 2005a; Chen et al., 2005b; Molyneaux et al., 2005). Neither *Fezf1* nor *Fezf2* is expressed in differentiated layer-IV neurons (Chen et al., 2005a; Chen et al., 2005b; Hirata et al., 2006b; Inoue et al., 2004; Molyneaux et al., 2005), but both are expressed in their progenitors (neural stem cells or intermediate progenitors). Layer-IV neurons are normally born (differentiated) from E13.5 through E15.5 (Molyneaux et al., 2007). Birthdate analysis indicated that *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon contained a reduced number of Rorb-positive neurons that were born at E13.5 (data not shown), suggesting that *Fezf1* and *Fezf2* control the generation of layer-IV neurons either from the neural stem cells or the intermediate progenitors. In *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon, differentiation of the neural stem cells into the TBR2$^{+}$ intermediate progenitors was impaired (Fig. 5). *Tbr2* is an essential regulator of the intermediate progenitors (Arnold et al., 2008; Sessa et al., 2008) and is directly regulated by neurogenin 2 (Ochiai et al., 2009). These data suggest that the gene cascade *Fezf1*/*Fezf2* ⊣ *Hes5* ⊣ neurogenin 2 regulates the expression of *Tbr2* and controls differentiation of the neural stem cells into the intermediate progenitors. The reduction of the TBR2$^{+}$ intermediate progenitors in the *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon might contribute to a reduction of layer-IV neurons. Consistent with this idea, *Hes5* deficiency rescued the development of TBR2$^{+}$ intermediate progenitors as well as layer-IV neurons in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon (Fig. 7). It is reported that TBR1$^{+}$ layer-VI neurons are increased in *Fezf2*$^{-/-}$ telencephalon (Molyneaux et al., 2005), suggesting the transfate of layer-V to layer-VI neurons. However, they were not increased in *Fezf1*$^{-/-}$*Fezf2*$^{-/-}$ telencephalon (Fig. 5), implying that the gene cascade *Fezf1*/*Fezf2* ⊣ *Hes5* ⊣ neurogenin 2 controls the generation of layer-VI neurons. Future studies will clarify these issues.

In summary, FEZF1 and FEZF2 are transcriptional repressors that repress *Hes5* expression and subsequently activate neurogenin expression. The *Fezf1*/*Fezf2* ⊣ *Hes5* ⊣ neurogenin 2 gene cascade controls differentiation of the neural stem cells into neurons or intermediate progenitors and contributes to the generation of a variety of neurons in the forebrain.

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**Competing interests statement**

The authors declare no competing financial interests.

**Supplementary material**

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