Signalling from hindbrain boundaries regulates neuronal clustering that patterns neurogenesis

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SUMMARY
During central nervous system development, neural progenitors are patterned to form discrete neurogenic and non-neurogenic zones. In the zebrafish hindbrain, neurogenesis is organised by Fgf20a emanating from neurons located at each segment centre that inhibits neuronal differentiation in adjacent progenitors. Here, we have identified a molecular mechanism that clusters fgf20a-expressing neurons in segment centres and uncovered a requirement for this positioning in the regulation of neurogenesis. Disruption of hindbrain boundary cell formation alters the organisation of fgf20a-expressing neurons, consistent with a role of chemorepulsion from boundaries. The semaphorins Sema3fb and Sema3gb, which are expressed by boundary cells, and their receptor Nrp2a are required for clustering of fgf20a-expressing neurons at segment centres. The dispersal of fgf20a-expressing neurons that occurs following the disruption of boundaries or of Sema3fb/Sema3gb signalling leads to reduced FGF target gene expression in progenitors and an increased number of differentiating neurons. Sema3 signalling from boundaries thus links hindbrain segmentation to the positioning of fgf20a-expressing neurons that regulates neurogenesis.

KEY WORDS: Boundaries, Neurogenesis, Segmentation, FGF signalling, Semaphorin

INTRODUCTION
The complex and stereotyped organisation of neurons in the central nervous system is established during development by the differentiation of progenitor cells in the neural epithelium, their migration to the correct location in the mantle zone, and the extension of axons to connect to appropriate targets. The initial steps require the strict regulation of cell differentiation such that the correct number of each neural cell type is formed while retaining sufficient progenitors to generate later-forming cell types. In part this is achieved through the action of inhibitory factors that limit the amount of differentiation in all progenitors (Bylund et al., 2003; Graham et al., 2003) and through Notch-mediated lateral inhibition within the neural epithelium, in which forming neurons inhibit the differentiation of their neighbours (Louvi and Artavanis-Tsakonas, 2006; Kageyama et al., 2007). In some regions of the neural epithelium, there is also a large-scale patterning of neurogenesis to form discrete neurogenic and non-neurogenic zones (Bally-Cuif and Hammerschmidt, 2003; Diez del Corral et al., 2003). For example, three neurogenic zones form along the dorsoventral axis of the spinal cord during primary neurogenesis due to inhibition of differentiation in the intervening regions by specific Hes/Her and Zic genes (Brewster et al., 1998; Bae et al., 2005). Similarly, a non-neurogenic zone forms at the midbrainhindbrain boundary due to the inhibitory action of Hes/Her family members (Geling et al., 2003; Geling et al., 2004). In these examples, the expression of transcription factors that inhibit neuronal differentiation appears to be linked to dorsoventral and anteroposterior patterning within the neural epithelium that underlies cell type and regional specification.

Another striking example of spatially restricted neurogenesis occurs within segments in the zebrafish hindbrain, where neuronal differentiation is absent at the boundaries and centre of each segment (rhombomere) and thus becomes confined to zones flanking each segment boundary (Cheng et al., 2004). Furthermore, specific neuronal and glial cell types are organised in a segmentally repeated pattern; for example, primary reticulospinal neurons are located at each segment centre (Hanneman et al., 1988) and the fibres of radial glial cells form a curtain that flanks segment boundary cells (Trevarrow et al., 1990). These observations raise the question of how the patterning of neurogenesis within segments is established. In view of the mirror-image symmetric organisation of neurogenesis around hindbrain boundaries, one possibility is that each boundary serves as a signalling centre that regulates cell differentiation, analogous to the roles of boundaries in the Drosophila wing disc (Irvine and Rauskolb, 2001; Tamagnone and Comoglio, 2004; Cavodeassi and Houart, 2012). Indeed, specialised boundary cells form at the interface of hindbrain segments that have distinct molecular and cellular properties (Guthrie and Lumsden, 1991; Heyman et al., 1995; Xu et al., 1995). The absence of neurogenesis at hindbrain boundaries might be due to Notch activation promoted by Rfng, which is expressed by boundary cells (Cheng et al., 2004; Qiu et al., 2004; Qiu et al., 2009). Apparent support for the role of a boundary signal in organising neurogenesis came from the effects of knockdown of Wnt genes expressed in hindbrain boundaries (Riley et al., 2004; Amoyel et al., 2005); however, later work revealed that the altered neurogenesis was due to non-specific activation of the Bcl-caspase pathway, which has a non-apoptotic role in hindbrain boundary cell formation (Gerety and Wilkinson, 2011).
A different hypothesis for how boundaries could underlie the patterning of hindbrain neurogenesis is suggested by studies that reveal a key role of fgf20a-expressing neurons, which are located in the mantle region at each segment centre and are required for formation of the non-neurogenic zone in the adjacent neural epithelium (Gonzalez-Quevedo et al., 2010). In fgf20a mutant embryos, ectopic neurogenesis occurs throughout segment centres, probably owing to a lack of inhibition of neuronal differentiation rather than to altered proliferation of a progenitor population, as FGf signalling does not affect hindbrain cell proliferation at these stages (Gonzalez-Quevedo et al., 2010). Concurrent with the inhibition of neurogenesis, FGf signalling may promote gliogenesis in segment centres (Esain et al., 2010) and thus underlie a switch in cell fate. These findings suggest that it is the localisation of fgf20a expression that forms a signalling centre in the mantle zone that underlies the stereotyped patterning of neurogenesis. We therefore set out to elucidate how fgf20a expression is restricted and, in particular, to address the possibility that it involves signalling from hindbrain boundaries.

By analysing the effects of disrupting hindbrain boundaries, we find that boundary cells are required to maintain a tight cluster of fgf20a-expressing neurons in each segment centre. We show that two semaphorin family members expressed at hindbrain boundaries, Sema3fb and Sema3gb, act through Nrp2a to position these fgf20a-expressing neurons in segment centres. The dispersal of these neurons that occurs upon disruption of semaphorin function leads to an abnormal organisation of neurogenesis and to an increase in the number of differentiating neurons. Hence, there is an interdependence between the stereotyped positioning of fgf20a-expressing neurons and the regulation of neurogenesis.

MATERIALS AND METHODS

Fish maintenance and transgenic and mutant zebrafish lines

Zebrafish embryos were obtained by natural spawning and raised at 28.5°C as described (Westerfield, 1993). The tp53 mutant line (Berghmans et al., 2005) was acquired from the Zebrafish International Resource Center (University of Oregon, Eugene, OR, USA).

Primers

Primers used were (5'-3'): Sema3fbFw(ClaI),ATAATCGATATGCTTCGAGGGAGCCACTTGGTCT; Sema3fbRf(BsuWI),ATACGTACGTCATGTCTCCTCCTCGTCCTCGCC; Sema3gbFw(ClaI),ATAATCGATATGCTCTCTGGTTCTCC; efnb3bEx1Fw,TTCCGAGTCC-TCATCTCTGCTTTTCGTCTTG; Sema3gbRe(BsiWI),ATACGTACGTCATGTCTCCTCCTCGTCCTCGCC; Sema3gbFw(ClaI),ATAATCGATATGCTCTCTGGTTCTCC; efnb3bEx1Fw,TTCCGAGTCC-TCATCTCTGCTTTTCGTCTTG; and efnb3bIn1Re,TAATGCGAGTGGACTCCTGCG.

Morpholino oligonucleotides

Morpholino oligonucleotides (MOs) were purchased from Gene Tools. One- to four-cell embryos were microinjected with 1.8 nl MO diluted to 5-10 ng/nl in water. All experiments were performed with at least two independent replicates, and injections with control MO were carried out on the same clutch as experimental injections. tp53−/− embryos were used for MO injections to avoid off-target gene expression caused by toxicity (Gerety and Wilkinson, 2011). The following MOs (5'-3') have been validated previously: ephaxa (AACACAAGCGCCAGCGCTGTC (Cooke et al., 2005); rfg (TGGAGGCGACATGGGATAATGCGAT) (Cheng et al., 2004); sema3gb (ATTCGCAAATTTTCACCATTTTGTTGA) (Yu and Moens, 2005); and sema3fb (CATAGACTGTCACAGAGCAATGGTCGTC) (Cooke et al., 2005); rfg (TGGAGGCGACATGGGATAATGCGAT) (Cheng et al., 2004); sema3gb (ATTCGCAAATTTTCACCATTTTGTTGA) (Yu and Moens, 2005); and sema3fb (CATAGACTGTCACAGAGCAATGGTCGTC) (Cooke et al., 2005); rfg (TGGAGGCGACATGGGATAATGCGAT) (Cheng et al., 2004); sema3gb (ATTCGCAAATTTTCACCATTTTGTTGA) (Yu and Moens, 2005); and sema3fb (CATAGACTGTCACAGAGCAATGGTCGTC) (Cooke et al., 2005).

Splice-blocking efnb3b MO (TTTGGGCTTCCTACCTTTGCTCAAG, efnb3b-SB MO) was used at 6 ng/nl. A scheme of the effect on transcript production is shown in supplementary material Fig. S1D. The efficacy of this MO was determined by RT-PCR analysis, which showed that efnb3b transcript splicing is blocked by efnb3b-SB MO but not control MO (supplementary material Fig. S1F). The loss of rfg expression in efnb3b-SB MO-injected embryos (supplementary material Fig. S1B) is similar to that observed in embryos injected with translation-blocking efnb3b MO (ACTCCCATCAAAGCGCGTGTGCGGGA; efnb3b-TB) (supplementary material Fig. S1C).

In situ hybridisation and immunohistochemistry

Embryos were grown at 28.5°C to the desired stage, fixed in 4% paraformaldehyde in PBS overnight, then stored in 100% methanol, or processed immediately for in situ hybridisation or immunohistochemistry. The in situ hybridisation probes for neurog1, rfg (Amoyel et al., 2005), fgf20a and efnb3b (Gonzalez-Quevedo et al., 2010) are as previously described. Based on published sequence information, PCR products were cloned as probe templates into pGemT-Easy (Promega, A1360) using the primers described above for sema3gb (AY766121), sema3fb (AY766119), npr2a (NM_212965.1) and npr2b (NM_212966.1). Digoxigenin-UTP-labelled riboprobes were synthesised according to the manufacturer’s instructions (Roche) and in situ hybridisation and colour development with NTB/BCIP were performed as described (Xu and Wilkinson, 1998). Fluorescent in situ hybridisations combined with NTB/BCIP were performed as described (Hauptmann and Gerster, 1994) with minor modifications. Colour detection was performed using Fast Red tablets (Roche, 11496549001).

For antibody staining after fluorescent in situ hybridisation, embryos were washed with PBS containing 0.1% Tween 20, then blocked in PBS containing 0.1% Tween 20 and 5% goat serum. Antibodies were diluted in this blocking solution and incubated overnight at 4°C. Rabbit anti-EphA4 (1:450) (Irving et al., 1996), rabbit anti-GFP (1:200; Torrey Pines, TP 401) and anti-HuC/D (1:200; Invitrogen, A21271) were used as primary antibodies and detected with Alexa Fluor 488, 594 or 647 goat anti-rabbit IgG (1:450; Invitrogen). Fluorescent images were captured using a Leica TCS SP2 confocal microscope.

Quantitations

Stacks of confocal images were collected of fgf20a-expressing neurons or HuC/D-expressing neurons, each combined with EphA4 immunocytochemistry to detect the location of segment interfaces. Images were processed with Fiji (Imagej) and Adobe Photoshop. To quantitate the distribution of fgf20a-expressing neurons, images of r3, r4 and r5 were processed to an identical size along the anteroposterior (AP) axis from one boundary to the next. A scheme of the procedure and examples of clusters in the different MO conditions are shown in supplementary material Fig. S4. The images were used for two quantitations: (1) the AP distance from the rhombomere centre to the furthest edge of the neuron cluster compared with the centre-boundary distance (r; 100 arbitrary units) and (2) the AP distance between the two edges of the cluster compared with the total rhombomere length (β; 100 arbitrary units).

To quantitate the fusion of r5 and r6 neurons in efnb3b morphants, stacks of confocal images were used to measure the AP distance from the posterior edge of the r5 fgf20a-expressing neuronal cluster to the anterior edge of the r6 cluster. Stacks of confocal images were used to count the number of Hu-expressing neurons or fgf20a-expressing neurons in r3-r5, and to measure the AP length of r3, r4 and r5 in the midline region. All data were processed with Microsoft Excel and the significance of results assessed using the two-tailed Student’s t-test.

RESULTS

The stereotyped organisation of neurogenesis within hindbrain segments in zebrafish can potentially be explained by a role of hindbrain boundary cells in restricting fgf20a expression to neurons (for brevity referred to hereafter as fgf20a neurons) located in the centre of segments. Such a role could be mediated through one of two alternative mechanisms: (1) that boundary cells are a source of signals that position neurons which intrinsically express fgf20a, or (2) that a diffusible signal emanating from boundary cells extrinsically represses fgf20a expression in the vicinity. These models can be assessed by analysing the effects of disrupting the formation of hindbrain boundary cells.
Loss of a subset of segment boundaries leads to repositioning of fgf20a neurons

As a first approach toward addressing the potential role of hindbrain boundary cells, we took advantage of the findings that Eph receptor and ephrin signalling not only underlies the formation of sharp segment interfaces, but also is required for the upregulation of boundary cell markers (Xu et al., 1995; Cooke et al., 2005). Knockdown of epha4a leads to decreased expression of the boundary cell marker sema3gb at some segment interfaces, but not others (Cooke et al., 2005), which is likely to reflect the overlapping expression and function of other Eph receptors. We verified this finding using rfng as a boundary cell marker and found loss or substantial downregulation of its expression at the interface between segments 2/3, 3/4 and 5/6, whereas expression was maintained at the 4/5 and 6/7 boundaries (Fig. 1A,B). We found that epha4a knockdown leads to an altered organisation of fgf20a-expressing cells at 24 hours postfertilisation (hpf): whereas fgf20a expression in rhombomere (r) 4 seemed unaffected, the cluster of fgf20a neurons in r3 was more dispersed, and in r5 and r6 the clusters were relocated and became fused near to the r5/r6 interface (Fig. 1D,E). As the altered organisation is not accompanied by an increase in the number of fgf20a neurons (Fig. 1N), these observations argue against boundary cells acting to repress fgf20a expression and are more consistent with a role in positioning of fgf20a neurons.

An alternative interpretation is that knockdown disrupts the organisation of fgf20a neurons in r3 and r5, where epha4a is normally expressed, due to a role of this Eph receptor within r3/r5 rather than in boundary cell formation. To address this, we knocked down ephrin B3b (efnb3b), a ligand of EphA4 (Gale et al., 1996), which is expressed in r2/r4/r6 (Chan et al., 2001), complementary to epha4a. We found that efnb3b knockdown leads to a similar disruption of boundary marker expression as epha4a knockdown (Fig. 1C; supplementary material Fig. S1), consistent with these factors acting as a receptor-ligand pair. By detecting Epha4a protein as a marker of r3/r5 following knockdown of efnb3b, we

Fig. 1. Disruption of a subset of rhombomere boundaries affects the position of fgf20a neurons. Brightfield and confocal images show dorsal views of the zebrafish hindbrain, anterior to the top, following in situ hybridisation (blue or red) and staining for EphA4 protein (green). (A-C) rfng expression in 21 ss embryos after injection of control MO (A), epha4a MO (B) or efnb3b-SB MO (C). There is decreased boundary marker expression selectively at the r2/r3, r3/r4 and r5/r6 borders following epha4a (90%, n=32) or efnb3b (82%, n=23) knockdown. (D,E) fgf20a expression at 24 hpf after injection of control MO (D) or epha4a MO (E). Knockdown of epha4a leads to altered localisation of fgf20a neurons (88%, n=26). (F-M) fgf20a expression (red) and EphA4 antibody staining (green) in embryos injected with control MO (F,G,I,J,K) or efnb3b-SB MO (H,I,L,M) at 18 ss (F-I) and 24 hpf (J-M). Arrow points to r5 and r6 fgf20a neuronal clusters that approach and fuse near to the r5/r6 interface. efnb3b morphants do not have the r5-r6 fusion of fgf20a neurons at 18 ss (95%, n=20), but do at 24 hpf (83%, n=18). (N) Quantitation of the number of fgf20a neurons in r5 plus r6. There is no significant difference between control versus efnb3b knockdown embryos (15.9±0.4 versus 15.1±0.3 neurons, average ± s.e.m., n=11 each; P=0.19). (O-Q) etv5b expression at 30 hpf in embryos injected with control MO (O), epha4a MO (P) and efnb3b-SB MO (Q). Knockdown of epha4a or efnb3b leads to an altered pattern with fewer stripes of etv5b expression (94%, n=35; 88%, n=24, respectively). Dashed white lines indicate the position of missing boundary marker expression, and continuous white lines indicate the position of remaining boundary cells. r, rhombomere.
visualised the relationship between fgf20a neurons and segment interfaces (Fig. 1F-M). We found that efnb3b knockdown leads to a similar alteration in the positioning of fgf20a neurons at 24 hpf as epha4a knockdown, with a dispersal of fgf20a neurons in r3 and an ectopic cluster at the r5/r6 interface (Fig. 1L,M). The r5/r6 clusters are separate at the 18-somite stage (ss) (Fig. 1H,I) but are fused by 24 hpf (Fig. 1L,M), suggesting that they undergo a progressive displacement from their original position at the centre of r5 and r6. The similar effect of knockdown of epha4a and efnb3b – which in the hindbrain interact only at segment borders – suggests that the altered organisation of fgf20a neurons is a consequence of the depletion of boundary cells rather than reflecting an autonomous role in the segments within which they are expressed. The finding that the organisation of fgf20a neurons in efnb3b morphants appears normal at early stages suggests that boundary cells are not required for the initial positioning of these neurons.

To determine whether the altered position of fgf20a neurons affects the pattern of FGF receptor activation, we analysed the expression of etv5b (erm), a target of Fgf20a signalling at this stage of development (Gonzalez-Quevedo et al., 2010). In control embryos, etv5b is restricted to the centre of each of the six rhombomeres (Fig. 1O). Knockdown of either epha4a (Fig. 1P) or efnb3b (Fig. 1Q) leads to a similar change, in which there are fewer stripes of etv5b expression, and these correlate with the altered position of fgf20a neurons in these knockdown conditions: there is strong etv5b expression in r4 and at the r5/r6 border where clustering of fgf20a neurons occurs, but expression is weaker in the other segments.

**Loss of all segment boundaries leads to dispersal of fgf20a neurons**

To further test the role of hindbrain boundary cells, we sought to disrupt their formation or maintenance independently of loss of Eph/ephrin signalling. Previous studies have shown that a deficiency...
of Notch activation leads to progressive depletion of hindbrain boundary cells, probably because Notch limits the differentiation of neural progenitors (Cheng et al., 2004; Qiu et al., 2009). rfng is a good candidate to be involved in boundary cell maintenance because its expression is restricted to rhombomere boundaries (Cheng et al., 2004; Qiu et al., 2004) and, by glycosylating Notch, Rfng promotes Notch activation in other contexts (Irvine and Wieschaus, 1994). We knocked down rfng and found that this leads to decreased boundary expression of her9, sema3gb and sema3fb (Fig. 2A,F), whereas borders of epha4a expression remain sharp (Fig. 2G,L). Unlike knockdown of epha4a or efnb3b, rfng knockdown disrupts boundary cell marker expression at all segment borders.

We found that rfng knockdown leads to alterations in the position of fgf20a neurons at 24 hpf (Fig. 2K-N) and in the pattern of etv5b expression, which becomes less localised to segment centres and/or decreases in level (supplementary material Fig. S2C). Whereas in control embryos the clusters of fgf20a neurons are at rhombomere centres (Fig. 2K,L), following rfng knockdown they are either closer to one of the boundaries or more spread out along the anteroposterior (AP) axis of the rhombomere (Fig. 2M,N). Quantitation of the number of fgf20a neurons revealed no significant change in rfng morphants (supplementary material Fig. S3A) and thus the altered organisation appears to be due to mispositioning rather than excess production. Unlike the situation in efnb3b morphants, we did not detect a systematic anterior or posterior movement of specific clusters. Since the organisation of fgf20a neurons in rfng morphants appeared normal at 18 ss (Fig. 2G-I), we conclude that boundaries are required to maintain rather than establish their positioning.

The altered distribution of fgf20a neurons varies between rfng morphants (supplementary material Fig. S4C) and even between the left and right sides of the same rhombomere (Fig. 2N). We quantitated and assessed the statistical significance of the changes (supplementary material Fig. 4A) by measuring the position of the anterior and posterior edges of the fgf20a neuron population in relation to the boundary-to-boundary length of each segment (which is not significantly altered in rfng morphants; supplementary material Fig. S3B). We used this to calculate the distance from the segment centre to the boundary occupied by fgf20a neurons. Whereas in control 24-hpf embryos fgf20a neurons occupy 55% of the centre-to-boundary distance, in rfng knockdown embryos they occupy 81% (Fig. 2O). We also measured the average length of the clusters along the AP axis and found that this increased from 45% in control embryos to 62% in rfng knockdown embryos (Fig. 2P). In contrast to this significant spreading at 24 hpf, there was little difference between control and rfng morphant embryos at 18 ss (Fig. 2O,P).

Semaphorins expressed at hindbrain boundaries maintain the positioning of fgf20a neurons

The migration of fgf20a neurons to the r5/r6 border following loss of epha4a or efnb3b function might be because boundary cells are depleted only at specific segment interfaces, as this phenotype is not seen following rfng knockdown, in which all boundaries are disrupted. If boundary cells are a source of a repellent cue, signalling from residual boundaries would act to relocalise fgf20a neurons, whereas depletion of all boundaries would decrease chemorepulsion and lead to a spreading of these neurons. Specifically, this model can explain why in epha4a and efnb3 knockdown embryos the fgf20a neurons in r5 and r6 move to the r5/r6 border, equidistant from the remaining boundary cells, although it does not account for the unaltered distribution of r4 neurons. This raises the question of whether hindbrain boundary cells express any chemorepellents. Semaphorins are good candidates to fit this role of a repellent because, in addition to roles in axon guidance, they have been implicated in directing the migration of neuronal cell bodies (Tamagnone and Comoglio, 2004; Ayala et al., 2007; Marin et al., 2010). Two members of this ligand family, sema3gb and sema3fb, are specifically expressed in rhombomere boundaries (Fig. 2B,C) and thus the altered organisation appears to be due to overlapping functions. By contrast, knockdown of sema3gb plus sema3fb led to spreading or mispositioning of fgf20a neurons (Fig. 3A-D; supplementary material Fig. S4D) and decreased or mislocalised etv5b expression (supplementary material Fig. S2,F), whether hindbrain boundary cells express any chemorepellents.
without any significant change in the number of these neurons (supplementary material Fig. S3A). Quantitation of the distribution of fgf20a neurons in sema3fb+sema3gb morphants reveals a significant increase in the distance that they occupy from segment centre to boundary and in the AP length of the cluster (Fig. 3E,F). The similar effect of knockdown of sema3fb+sema3gb and rfg, in which the clusters of fgf20a neurons are mislocalised or spread out towards boundaries, is consistent with these semaphorins acting as the proposed repellent cues. The remaining segmental expression of sema3fb in r3 and r5 might explain why the fgf20a neurons in r4 are not mislocalised in epha4a knockdown embryos despite the depletion of anterior boundary cells of this segment.

To further address the role of sema3fb and sema3gb in positioning fgf20a neurons, we analysed the expression and role of their receptors, nrp2a and nrp2b. We found that nrp2a expression at segment centres (Yu et al., 2004; Yu and Moens, 2005) is coincident with fgf20a expression, whereas nrp2b is not expressed (supplementary material Fig. S5). Following nrp2a knockdown (but not nrp2b knockdown), fgf20a neurons are more spread out and closer to the boundary (Fig. 4A-D, quantitation in 4E,F; supplementary material Fig. S4E), but do not significantly change in number (supplementary material Fig. S3A).

**sema3fb+sema3gb or nrp2a knockdown alleviates fgf20a neuron migration induced by disrupting a subset of boundaries**

The finding that, following epha4a or efnb3b knockdown, fgf20a neurons in r5 and r6 become relocosed to the r5/r6 border might be explained by chemorepulsion from the boundary cells, which remain at the r4/r5 and r6/r7 interfaces. This model predicts that knockdown of sema3fb+sema3gb will rescue the mislocalisation of these cells following efnb3b knockdown. We carried out knockdown of efnb3b and visualised segment borders by detection of Epha4A, and, as shown above, found that the fgf20a-expressing clusters in r5 and r6 are now located closer to the r5/r6 border at 24 hpf (Fig. 4LJ) than in controls (Fig. 4G,H). However, when efnb3b knockdown is combined with sema3fb+sema3gb knockdown, there is less movement of fgf20a neurons towards the r5/r6 border and the r5 and r6 clusters do not collide (Fig. 4K,L, quantitated in 4O). Instead, the fgf20a neurons are more spread out both anteriorly and posteriorly, a characteristic of knockdown of sema3fb+sema3gb. Similarly, nrp2a knockdown decreased the movement of fgf20a neurons towards the r5/r6 border in efnb3b morphants (Fig. 4M-O). These results confirm that Sema3fb and Sema3gb act through their common receptor Nrp2a as repellent cues that position fgf20a neuronal clusters at segment centres.

**Dispersal of fgf20a neurons leads to increased neurogenesis**

Previous work showing that fgf20a suppresses neurogenesis at segment centres (Gonzalez-Quevedo et al., 2010) implies that the appropriate positioning of fgf20a neurons is required to achieve the correct patterning of neurogenesis. Indeed, we find that knockdown of rfg, sema3fb+sema3gb, or nrp2a each leads to disorganisation of the non-neurogenic zone, as marked by a lack of neurog1 expression (Fig. 5A-D). To examine whether the dispersal of fgf20a neurons following loss of hindbrain boundary cells affects the overall amount of neurogenesis, we detected HuC/D (Elavl3/4) protein, which marks all differentiating neurons in the mantle zone, and quantitated the number of expressing cells in confocal stacks throughout the dorsoventral axis. We found that knockdown of rfg, sema3fb+sema3gb, or nrp2a led to a 30-60% increase in the number of neurons (Fig. 5E-H, quantitated in 5M). The pattern of HuC/D staining in these morphants retains a segmented distribution, with a gap around hindbrain boundaries; this is likely to reflect persistence of the curtains of radial glial fibres that flank boundaries and physically exclude neurons (Trevorrow et al., 1990).

A potential explanation for the increased neurogenesis following the dispersal of fgf20a neurons is suggested by the observation that, in epha4a and efnb3b knockdown embryos, expression of the FGFindicator morphant eph4a target gene ev5b occurs at high levels in r4 and at the r5/r6 border, but at lower levels in all other hindbrain segments (Fig. 1P,Q). This pattern of ev5b expression correlates with the clustering of fgf20a neurons in r4 and the r5/r6 border, and suggests that the dispersal of these neurons in the other segments leads to a lower level of FGF pathway activation. We quantified HuC/D-expressing neurons within hindbrain segments following efnb3b knockdown and found a significant increase in r3 (13%) and decrease in r5 (13%), whereas r4 was unaffected (Fig. S1-L, quantitated in S5N). The amount of neurogenesis thus correlates with the organisation of fgf20a neurons, which in efnb3b morphants are dispersed in r3, clustered normally in r4, and form a fused cluster of r5 and r6 neurons at the r5/r6 border.

**DISCUSSION**

Previous studies have shown that neurogenesis is spatially organised within hindbrain segments in zebrafish through the FGF-mediated inhibition of neurogenesis (Gonzalez-Quevedo et al., 2010). This inhibition is due to signalling from the mantle zone by fgf20a neurons located at each segment centre that underlies the formation of a non-neurogenic zone in the adjacent progenitor cells. These findings suggested that the stereotyped location of fgf20a neurons at segment centres might be important for the patterning of neurogenesis, and raise the question of how this positioning is achieved. Here, we have uncovered a mechanism in which signalling from hindbrain boundaries maintains the tight clustering of neurogenic zone precursors in the neural epithelium.

The results of loss-of-function experiments implicate Sema3fb and Sema3gb, which are expressed in hindbrain boundaries, in positioning fgf20a neurons by acting through their common receptor Nrp2a. Consistent with this, we find that sema3fb+sema3gb knockdown alleviates the abnormal migration of fgf20a neurons towards the depleted r5/r6 boundary in efnb3b morphants. These findings are consistent with a model in which hindbrain boundary cells are a source of semaphorin signals that chemorepel fgf20a neurons towards segment centres where they are furthest from the flanking borders, leading to inhibition of neurogenesis in the adjacent progenitors (Fig. 6A,B). The tight
clustering of fgf20a neurons has an important role in the patterning of neurogenesis: when it is disrupted following knockdown of rfng, sema3fb+sema3gb or nrp2a the organisation of the neurogenic and non-neurogenic zones is altered (Fig. 6C,D).

Our findings raise the question of how the cluster of fgf20a neurons spreads out and becomes mislocalised in a variable pattern following the disruption of hindbrain boundaries or of sema3fb/sema3gb function. This might be associated with the major expansion of the mantle region as differentiating neurons migrate in from the neural epithelium, as well as with the overall growth of neural tissue. This growth has the potential to drive cell intercalation that separates neighbours, such that repeated rounds of intercalation lead to a variable spreading of cells that are initially clustered.

**Roles of boundaries in patterning**

One of the important roles of boundary formation during development is to generate specialised boundary cells that are a source of inductive signals that regulate cell differentiation in a
concentration-dependent manner (Dahmann and Basler, 1999; Irvine and Rauskolb, 2001; Kiecker and Lumsden, 2005). Our findings reveal a distinctive role of hindbrain boundaries in which, by acting as a source of chemorepellent, they serve to position another signalling source – \textit{fgf20a} neurons – that patterns cell differentiation. It remains possible that other signals emanating from hindbrain boundaries have an inductive role in which they promote the differentiation of adjacent progenitors, such that the neurogenic zone is positioned by antagonistic inductive and inhibitory signals. However, this seems unlikely because neurogenesis does not decrease – on the contrary, it increases – following depletion of boundary cells. Thus, other boundary signals, such as Wnt family members (Riley et al., 2004; Amoyel et al., 2005), are not essential for neuronal differentiation and might regulate other aspects of hindbrain development.

\textbf{Neuronal organisation and neurogenesis}

The precise positioning of neuronal cell types and their organisation into clusters are ubiquitous aspects of nervous system development. This positioning requires the radial migration of neuronal cell bodies from the neural epithelium, and in some cases tangential migration over long distances, guided by contact-dependent or diffusible cues that include semaphorins (Ayala et al., 2007; Marín et al., 2010). The significance of such migration to position neuronal cell bodies at a particular location is unclear, but
is thought to facilitate the formation of functional neuronal circuits (Chen et al., 2006). In the case of reticulospinal neurons, which are located at segment centres in the hindbrain (Hanneman et al., 1988), these are components of an early neuronal circuit that underlies an escape response (Liu and Fetcho, 1999). Our findings suggest another type of role for neuronal clustering.

We find that depletion of hindbrain boundary cells leads to a significant increase in the overall amount of neurogenesis, albeit that this requires other factors to account for the normal formation of neurogenic zones adjacent to boundaries. However, increased neurogenesis also occurs following disruption of Sema3fb/Sema3gb signalling, in which hindbrain boundary cells remain present. These findings argue for a model in which the clustering of fgf20a neurons is required for the correct patterning and amount of neurogenesis. We find that the spreading of fgf20a neurons along the AP axis that occurs following the disruption of boundaries or of Sema3fb/Sema3gb signalling does not lead to a wider non-neurogenic zone, but rather correlates with an increase in the overall amount of neurogenesis. A potential explanation is suggested by the observation that, following epha4 or efnb3b knockdown, expression of the FGF-response gene etv5b remains at a high level in r4 and at the r5/r6 border where clustering of fgf20a neurons still occurs, but is at lower levels in all of the other segments. This suggests that clustering of Fgf20a signalling cells is required to achieve a high level of FGF signal and target gene activation. We therefore propose that neuronal differentiation is inhibited above a threshold level of PGF pathway activation in progenitor cells, and that this requires the tight clustering of fgf20a neurons to provide a focussed source of FGF signals. This is reminiscent of the situation for signalling centres that are induced at boundaries, which require that the border is sharp and straightforward in order to achieve the appropriate distribution of the graded signal (Dahmann and Basler, 1999). Our findings thus provide a further perspective on the mechanistic importance of establishing a precise organisation of signalling cells and how this can be achieved.

Acknowledgements
We thank James Briscoe and Francois Guillemot for helpful discussions and comments on the manuscript and NIMR Biological Services for zebrafish husbandry.

Funding
This work was supported by the UK Medical Research Council [U117532048] and by postdoctoral fellowships from the European Commission Marie Curie Programme (J.T. and R.G.-Q.) and the Japan Society for the Promotion of Science (T.W.-A.). Deposited in PMC for release after 6 months.

Competing interests statement
The authors declare no competing financial interests.

Supplementary material
Supplementary material available online at http://dev.biologists.org/lookup/suppl/doi:10.1242/dev.080135/-/DC1

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