RESEARCH ARTICLE

Opposing Shh and Fgf signals initiate nasotemporal patterning of the zebrafish retina

María Hernández-Bejarano1,*, Gaia Gestri2,*, Lana Spawls2, Francisco Nieto-López1, Alexander Picker3, Masazumi Tada2, Michael Brand3, Paola Bovolenta1,4, Stephen W. Wilson2,‡ and Florencia Cavodeassi1,4,‡

ABSTRACT

The earliest known determinants of retinal nasotemporal identity are the transcriptional regulators Foxg1, which is expressed in the prospective nasal optic vesicle, and Foxd1, which is expressed in the prospective temporal optic vesicle. Previous work has shown that, in zebrafish, Fgf signals from the dorsal forebrain and olfactory primordia are required to specify nasal identity in the dorsal, prospective nasal, optic vesicle. Here, we show that Hh signalling from the ventral forebrain is required for specification of temporal identity in the ventral optic vesicle and is sufficient to induce temporal character when activated in the prospective nasal retina. Consequently, the evaginating optic vesicles become partitioned into prospective nasal and temporal domains by the opposing actions of Fgfs and Shh emanating from dorsal and ventral domains of the forebrain primordium. In absence of Fgf activity, foxd1 expression is established irrespective of levels of Hh signalling, indicating that the role of Shh in promoting foxd1 expression is only required in the presence of Fgf activity. Once the spatially complementary expression of foxd1 and foxg1 is established, the boundary between expression domains is maintained by mutual repression between Foxd1 and Foxg1.

KEY WORDS: Retina, Nasotemporal patterning, Shh, Fgfs, Zebrafish

INTRODUCTION

Our ability to perceive the world around us and to represent visual information accurately requires correctly mapped innervation of the primary visual centres in the brain by retinal ganglion cell (RGC) axons. Map formation depends on the acquisition of specific positional identities by RGC precursors, as this information underlies the ability of RGC axons to connect appropriately within central targets (Erskine and Herrera, 2007; Schulte and Bumsted-O’Brien, 2008). The allocation of nasotemporal (NT) and dorsoventral (DV) positional identities in the eye primordium is already apparent at the optic vesicle stage, long before the first RGCs’s differentiate (Hatini et al., 1994; Picker et al., 2009). In fish, prospective retinal cells destined to form the nasal retina are initially located dorsally in the evaginating optic vesicle, whereas prospective temporal retina is located ventrally (Fig. 1A; Picker et al., 2009). A topologically similar organisation is probably present in other vertebrates with nasal retina originating next to dorsal telencephalic forebrain and temporal retina next to ventral, hypothalamic forebrain (Cobos et al., 2001).

The earliest known transcriptional determinants of NT identity are Foxg1 and Foxd1, which show complementary patterns of expression in prospective nasal and temporal domains of the eye primordium, respectively (Hatini et al., 1994). By a combination of loss- and gain-of-function approaches, foxg1 has been shown to control cell proliferation and acquisition of nasal character during retinal patterning in mouse, chick, frog and zebrafish (Bourguignon et al., 1998; Hardcastle and Papalopulu, 2000; Huh et al., 1999; Martynoga et al., 2005; Picker et al., 2009). Complementarily, foxd1 promotes acquisition of temporal character (Carreres et al., 2011; Herrera et al., 2004; Takahashi et al., 2009, 2003).

In zebrafish, genes encoding the Fgf ligands Fgf8, Fgf3 and Fgf24 are expressed in the forebrain and ectoderm dorsal to the evaginating optic vesicles, and collectively they promote foxg1 expression and nasal identity in the dorsal optic vesicle (Picker and Brand, 2005; Picker et al., 2009). In the absence of Fgf activity, foxg1 expression is lost, whereas, conversely, foxd1 expands within the ventral half of the optic vesicle when the Fgf pathway is ectopically activated in this domain. The temporal determinant foxd1 responds to Fgf activity in the opposite way. However, although foxd1 expression expands into the dorsal optic vesicle in the absence of Fgfs, ectopic activation of Fgf activity in the ventral optic vesicle does not completely abrogate foxd1 expression from this domain (Picker and Brand, 2005; Picker et al., 2009). These observations suggest that, in addition to Fgfs, other signals are involved in establishment of NT regionalisation and complementary foxg1/foxd1 expression domains. In chick, for example, Wnt3a seems to modulate the expression of these genes, although a role for the Wnt pathway in controlling NT patterning has not been clearly demonstrated (Takahashi et al., 2009).

shh is expressed along the ventral midline of the forebrain in proximity to ventrally positioned, prospective temporal cells within the evaginating optic vesicles (Barth and Wilson, 1995; see also Fig. 3E). Shh is a morphogen and can generate a gradient of activity that confers different cellular identities according to the levels of ligand and the duration of the signal (Briscoe and Therond, 2013). Consequently, prospective temporal retinal cells may be exposed to Shh during the early phases of optic vesicle evagination and this pathway could therefore influence retinal NT patterning, together with Fgfs.

Although a role for Hh signalling in NT patterning has not been studied, this pathway does influence proximodistal (PD) regionalisation of the evaginated optic vesicle into optic stalk- and retina-forming territories (Ekker et al., 1995; Macdonald et al.,

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Absence of Shh signalling is associated with loss of the optic stalk and cyclopia (Chiang et al., 1996; Macdonald et al., 1995; Varga et al., 2001). Conversely, excessive Shh signalling in the distal, prospective retinal portion of the optic vesicle interferes with retinal specification and promotes an expansion of proximal retinal and optic stalk fates (Cardozo et al., 2014; Ekker et al., 1995; Macdonald et al., 1995; Perron et al., 2003). Shh is also proposed to control DV regionalisation within the retina by promoting the expression of the ventral retinal determinant Vax2 (Lupo et al., 2005; Take-uchi et al., 2003).

In this study, we show that Shh activity is required to activate foxd1 expression and to initiate temporal retinal identity at the onset of optic vesicle evagination in the zebrafish. Conditions in which Hh activity is lost result in the downregulation of foxd1 expression. Conversely, ectopic Hh activity in the dorsal optic vesicle activates foxd1 and represses foxg1 in this domain. The changes in foxg1/foxd1 expression upon activation of Hh signalling in evaginating optic vesicles result in altered NT retinal regionalisation and, as a consequence, abnormal targeting of retinal axonal projections in the tectum. Together with previous data, our study shows that NT patterning of the prospective retina is initiated in the optic vesicles by the opposing actions of the Fgf and Shh pathways. Although loss of Shh signalling leads to compromised specification of temporal identity and loss of Fgf signalling to compromised nasal identity, optic vesicles in which both pathways are blocked show recovery of foxd1 expression, indicating that in the absence of Fgf activity the role of Shh in promoting temporal identity is dispensable. Overall, our results suggest that it is the appropriate balance between Shh and Fgf signals that ensures appropriate NT regionalisation in the forming eyes.

**RESULTS**

**Abrogation of Hh signalling activity results in loss of temporal optic vesicle identity**

At early stages of eye formation, cells destined to contribute to temporal retina are positioned ventrally as the optic vesicle evaginates from the forebrain (Fig. 1A). We hypothesised that signals emanating from ventral midline tissue of the forebrain may impart temporal character to prospective retinal cells. Among such candidate signals are Shh and Twhh (Shhb – Zebrafish Information Network), both of which are Hh signalling proteins expressed prominently in ventral forebrain tissue adjacent and ventral to the evaginating optic vesicles (Barth and Wilson, 1995; Ekker et al., 1995). Consequently, we assessed whether the expression of foxd1, the earliest known marker of prospective temporal retina is influenced by Hh signalling.

Abrogation of Hh activity in smu mutants (which lack function of the Smoothened Hh co-receptor; Varga et al., 2001) or in syu mutants (which lack Shh function; Schauerte et al., 1998) resulted in loss or downregulation, respectively, of foxd1 expression in the ventral optic vesicle (Fig. 1B,F; data not shown). foxg1 is normally expressed in prospective nasal retina in a spatially complementary pattern to foxd1 (Fig. 1C,E). However, despite the absence of foxd1 expression, foxg1 expression did not expand into the ventral region
of the optic vesicle in Hh pathway mutants (Fig. 1D,G). Together, these results suggest that initiation of temporal retinal identity requires Hh signalling but that acquisition of nasal identity requires more than just the absence of Hh activity.

Temporally controlled modulation of Hh activity using the Smo antagonist cyclopamine (Chen et al., 2002; Taipale et al., 2000) revealed that signalling is required in a narrow window at the start of optic vesicle evagination to promote foxd1 expression. Although cyclopamine treatment starting at the 6-somite stage (ss) did not show any effect on foxd1 expression or temporal fate specification (Fig. S1A-D), treatment from 1-3ss onwards resulted in a complete loss of foxd1 expression (Fig. 1H,I) as well as of the H6n42A::GFP transgene (Picker et al., 2009), which specifically labels the temporal half of the eye primordium (Fig. S1E,F). Expression of the nasal markers foxg1 and the -8.0claudinb::lynGFP/foxg1 transgene (Haas and Gilmour, 2006) were not overtly affected by these treatments (Fig. 1J,K; Fig. S1J), a result consistent with the phenotype observed in sma and syu mutants. These results indicated that the Hh pathway is required between 1-3 and 6ss to promote temporal specification. At this stage, the optic vesicles are just starting to evaginate, but expression of foxd1 and foxg1 is already spatially restricted to complementary domains of the primordium (Fig. 1L,M).

**Ectopic Hh activity suppresses nasal and expands temporal identity in the optic vesicles**

The results described above indicated that Hh signalling is required to induce temporal identity at an early stage of optic vesicle development. To assess whether Hh activity is sufficient to promote foxd1 expression and temporal identity, we expressed UAS:shh in the early, evaginating optic primordium by use of a Gal4 driver (Tg{rx3::Gal4}) expressed in the eye field and evaginating optic vesicles (Weiss et al., 2012). This approach did not interfere with the establishment of primary subdivisions in the forebrain, as revealed by the largely normal telencephalic expression of foxg1 (compare Fig. 2A and 2B) and the optic vesicle and midbrain marker mab2112 (Fig. S2A,B).

Expression of Shh throughout the evaginating optic vesicles resulted in expansion of foxd1 expression and repression of foxg1 expression in the optic primordia but not in the adjacent telencephalon (Fig. 2A-D,II). The same effect within the optic vesicle was observed when we mosaically overexpressed Shh in subsets of eye field cells, or when Shh was overexpressed at low levels throughout the whole embryo (Fig. S3A-D'). Broad overexpression of ptch2 confirmed that the exogenous Shh in these experiments ectopically activates the Hh pathway (Fig. S3E,G).

The enhanced expression of foxd1 at the expense of foxg1 in the presence of excessive Hh signalling suggested an expansion of temporal character in the optic primordium. To assess whether this change is reflected in the NT character of differentiated RGCs, we analysed the topology of retina-to-tectal projections by lipophilic dye labelling of nasal and temporal axons of wild-type and Tg{rx3::Gal4};UAS:shh retinae. Nasal projections in wild-type 6 days post-fertilisation (dpf) fry innervated posterior regions of the tectum and clearly segregated from temporal projections (Fig. 2E). By contrast, nasal projections in Tg{rx3::Gal4};UAS:shh retinae targeted more anterior regions of the tectum and partially overlapped with projections from the most temporal part of the retina (Fig. 2F). This suggests that nasally positioned RGCs acquire temporal identity after early exposure of the optic vesicle to Hh activity. This character of temporal identity in the optic vesicle in Hh pathway mutants (Fig. 2D,G). Together, these results suggest that initiation of temporal retinal identity requires Hh signalling but that acquisition of nasal identity requires more than just the absence of Hh activity.

**Fgf does not appear to affect levels of Hh signalling whereas Hh activity promotes Fgf signalling**

Previous studies have shown that Fgf signalling promotes nasal identity in the optic vesicles; abrogation of Fgf activity results in the loss of nasal identity and the concomitant expansion of temporal fate (Picker and Brand, 2005; Picker et al., 2009). Thus, whereas loss of Fgf activity results in a transformation of nasal into temporal identity, loss of Hh activity instead leads to a loss of temporal character that is not accompanied by acquisition of nasal character. A possible contributory factor to these phenotypes would be cross regulation of Hh and Fgf signalling pathways. Consequently, we analysed expression of fgf8 and the Fgf pathway target sprouty4 in Hh loss-of-function embryos, and that of shh and the Hh target transgene ptch2::kaede (Huang et al., 2012), after interference with Fgf signalling.

Blocking Fgf signalling with the antagonist SU5402 (Mohammadi et al., 1997) from 1-2ss onwards efficiently transformed nasal to...
temporal character in the optic vesicle, as revealed by expanded foxd1 and loss of foxg1 expression (Fig. 3A-D; Picker et al., 2009). However, neither the expression of shh nor that of the ptch2::GFP transgene was affected by this treatment (Fig. 3E-H), suggesting that in the absence of Fgf signalling, Hh activity is largely unaffected.

Conversely, the level of Hh activity does affect Fgf signalling as cyclopamine treatments reduced the levels of both fgf8 and sprouty4 expression (Fig. 3I-L). This observation may help to explain why in the absence of Shh, nasal identity does not expand because there may be insufficient levels of inducer (Fgf) in the ventral portion of the optic vesicle to activate foxg1.

Simultaneous abrogation of Fgf and Hh partially rescues NT patterning

Our results indicate that Hh activity is necessary and sufficient to promote foxd1 expression in the optic vesicle. Furthermore, the observation that foxg1 does not expand when Hh activity is downregulated suggests that nasal and temporal identities might be established independently from each other by Fgf and Hh signals, respectively. If so, one might expect that simultaneous abrogation of Fgf and Hh activity should then lead to the absence of both nasal and temporal character. To test this hypothesis, we simultaneously abrogated Fgfs and Hhs by making use of two different approaches: analysis of double mutants for fgf8 (acerebellar; ace) and smu; and combined treatment with the pathway antagonists cycloamine and SU5402.

Contrary to expectation, simultaneous abrogation of Hh and Fgf signals led to a surprising recovery of NT patterning. Thus, whereas cycloamine treatment alone led to absence of foxd1 expression (Fig. 1H,I), when combined with SU5402, expression of foxd1 and the HGn42A::GFP transgene was restored within the prospective temporal retina (Fig. 4A-D; Fig. S1H). A similar result is observed in ace;smu double mutants (Fig. S4D,E). This implies that Hh signalling is only needed for induction of temporal character when Fgf signalling is active (and that Fgf activity represses foxd1 independently of Foxg1). This result cannot be explained by a failure of the drugs to work when in combination as expression of the pathway reporters ptch2 and sprouty4 is largely lost following cycloamine+SU5402 treatments (Fig. 4E-H). Thus, simultaneous loss of Hh and Fgf activity compromises NT patterning less than manipulation of just one of these signals, suggesting that NT patterning is influenced by the correct balance of both signals, and not by their absolute levels.

Similar to the observed restoration of temporal character, there was partial restoration of nasal foxg1 expression upon abrogation of both Hh and Fgf signals (Fig. 4A,B; Fig. S1L; Fig. S4), which is more complete in ace;smu mutants than in fish treated with cycloamine+SU5402 (compare Fig. 4B with Fig. S4D), as also confirmed by statistical analysis (Fig. S4A-C). This difference is probably due to the fact that in ace;smu double mutants Fgf abrogation is only partial, as the presence of Fgf3 and Fgf24 still probably activates the Fgf pathway (Picker et al., 2009). As expression of foxg1 was not fully restored in the absence of both Fgf and Hh signals, it suggests a more important role for Fgf signals in promoting nasal character than Hh signals in promoting temporal character. This result, together with the fact that foxg1 does not expand to the temporal retina in the absence of Hh (Fig. 1J,K), further reinforces the idea that Hh does not directly repress foxg1.

The abrogation of Fgf and Hh activities simultaneously from 1ss resulted, as shown above, in a partial recovery of the NT pattern. This suggests that earlier signalling events might be establishing foxd1/foxg1 expression. To assess whether even earlier modulation of the Hh and Fgf signalling pathways affects the spatially restricted expression of foxd1/foxg1 in the optic vesicle, we simultaneously abrogated Fgf and Hh signalling from mid-gastrulation, well before NT patterning is established.
Cyclopamine + SU5402 treatments from mid-gastrulation result in a dramatic expansion of foxd1 and complete loss of foxg1 expression within the optic vesicle (Fig. 4I,J), a phenotype comparable to that obtained by treatment with SU5402 alone [treatment from mid-gastrulation with only one drug at a time led to phenotypes very similar to those obtained with treatments at 1ss (not shown)]. This result supports the idea that Hh activity is fully dispensable for induction of foxd1 expression in the absence of Fgf signalling. It suggests that Hh signalling prevents repression of foxd1 by the Fgf signalling pathway, and, in this way, promotes temporal identity.

To further explore cross-regulation between Fgf and Hh pathways, we analysed NT patterning in cavefish (Astyanax mexicanus) embryos in which levels of Fgfs and shh vary between surface fish and cavefish forms. The species Astyanax mexicanus has a surface form, which lives in rivers and lakes, and a cavefish form, which lives in caves. These two populations were isolated from each other ∼10,000 years ago, and since then they have evolved divergently. The cavefish form has undergone a number of morphological changes in the forebrain, which seem to have their origin in subtle changes in expression patterns of regulatory genes during forebrain development (Pottin et al., 2011). One of these changes is an increased level of shh and precocious expression of fgf8 in the forebrain of the cavefish form in comparison to the surface fish form. Thus, cavefish present the opportunity to assess the effect of contemporaneously higher levels of fgf8 and shh on NT patterning of the optic vesicles. We reasoned that if Shh counteracts the repressive activity of Fgfs upon foxd1 expression, then higher levels of both signals may not compromise NT patterning. Indeed, cavefish optic vesicles show similar levels of foxg1 and foxd1 expression compared with surface fish (Fig. 4K-N), indicating that concomitant upregulation of the Hh and Fgf pathways does not overtly affect NT patterning. Together, these results support the idea that it is the relative, rather than the absolute, levels of these two signals that influence the establishment of NT identity.

Mutual repression between foxg1 and foxd1 maintains the border between nasal and temporal domains

Our results indicate that Fgf and Hh signals work in concert to promote mutually exclusive expression of foxg1 and foxd1 in the nasal and temporal retina, respectively. Previous studies in chick and mouse suggest that foxd1 and foxg1 can repress each other. For example, Foxd1 expression expands into the nasal half of the optic vesicle in Foxg1 mouse mutants (Huh et al., 1999), and misexpression of Foxd1 or Foxg1 interferes with the expression of the complementary gene in chick (Takahashi et al., 2009, 2003). To assess whether Foxg1 and Foxd1 cross-repress each other in zebrafish, we manipulated the levels of foxg1 and foxd1 in the optic vesicle through use of the Gal4/UAS approach as described above. Ectopic expression of foxg1 in the temporal half of the optic vesicle strongly downregulated foxd1 (Fig. 5A,B); conversely, foxd1 expression in the nasal part of the optic vesicle downregulated foxg1 expression (Fig. 5C,D). Thus, reciprocal repression between foxg1 and foxd1 occurs in fish as in other vertebrates. During normal development, the only position at which transcriptional cross-regulatory competition between Foxd1 and Foxg1 is likely to influence foxg1 and foxd1 expression is around the NT boundary where cells may receive sufficient Shh and Fgf signals to induce both genes.

**DISCUSSION**

This study uncovers a novel role for Shh in initiating the expression of the temporal fate determinant foxd1 in the ventral half of the...
from our manipulations. (F) Representative Tg (rx3:Gal4); UAS:foxg1 embryo showing widespread GFP expression in the optic vesicles. All embryos selected for in situ analysis showed similarly broad GFP expression. Scale bar: 100 μm. Numbers in the bottom-right of each panel indicate the number of embryos with the phenotype shown out of the total number of embryos analysed. Dashed lines outline the forebrain.

evaginating optic vesicles. Consequently, an interplay between Hh signals and Fgfs, which promote foxg1 expression in the dorsal, prospective nasal half of the optic vesicle, establishes NT pattern in the nascent optic primordium. Our results indicate that these two signals establish temporal and nasal identity at least in part independently of each other and that, once established, the boundary between nasal and temporal domains is maintained by mutual transcriptional repression between Foxd1 and Foxg1 (Fig. 6).

**Similarities to, and differences from, other patterning systems involving Fgfs and Shh**

The role for Shh and Fgfs that we describe for NT patterning of the optic vesicle is similar to that for anterior-posterior (AP) patterning of the otic vesicle, the primordium for the vertebrate ear. Fgfs, expressed rostral to the otic vesicle, promote anterior identity, whereas Shh, released by the tissues underlying the ear primordium, induces posterior identity (Hammond et al., 2003, 2010; Hammond and Whitfield, 2011). Manipulation of the levels of these two pathways affect AP patterning in the otic vesicle in a reciprocal way: loss of Fgf activity results in loss of anterior identity and the development of a double-posterior primordium; conversely, loss of Hh activity results in loss of posterior identity and the development of a partial double-anterior primordium. However, double loss of Hh and Fgfs results in an otic vesicle with neither anterior nor posterior identities, whereas in the optic vesicles NT patterning is partially recovered in such conditions.

Loss of both Shh and Fgf from mid-gastrula stage leads to absence of foxg1 expression, indicating that Fgf activity from gastrula stages onwards promotes subsequent expression of foxg1 expression in the prospective nasal retina. In addition, in these conditions foxd1 expression expands throughout the optic vesicle, reinforcing the idea that Shh is dispensable for foxd1 expression, provided there is no Fgf activity. Thus, acquisition of temporal identity normally requires the activity of Shh from as early as neural plate stages, to counteract Fgf-dependent repression of foxd1 expression.

The recovery of foxd1 expression in the optic vesicle in conditions in which both Fgf and Shh are abrogated is not the only situation in which loss of Hh activity can be compensated by following additional genetic changes. In the spinal cord, graded responses to Shh establish ventral neuronal identities and, consequently, ventral fates are lost upon removal of Shh activity (reviewed by Cohen et al., 2014; Dessaud et al., 2008). Ventral identities are, however, largely recovered when the function of the Gli3 transcriptional repressor of Hh target genes is also removed (Persson et al., 2002). Thus, acquisition of ventral spinal cord cell type identities can occur in a Shh-independent mechanism. This reveals a remarkable robustness in the establishment of DV patterning in the neural tube and NT patterning in the optic vesicle, and suggests the presence of compensatory mechanisms that can bypass requirement for Hh signalling.

A surprising aspect of the retinal NT phenotype following abrogation of both Shh and Fgf is the implication that Fgf is required for repression of foxd1 expression in the temporal retina independently of Foxg1 (and in addition to the Fgf-dependent repression of foxd1 in nasal retina that could be mediated through Foxg1; Fig. 5A,B). At least at the stages when optic vesicles initiate Fox gene expression, Fgf targets do not appear to be expressed in the prospective temporal domain (Picker et al., 2009; M.H.-B., F.C., G.G. and S.W.W., unpublished observations). This implies either that the Fgf pathway is activated earlier in this domain, or, if at the stage when Fox genes are induced, at sufficiently low levels so as to not activate expression of foxd1. An alternative possibility is that the repression is indirect and dependent upon non-autonomous consequences of Fgf activity in nasal retina. Although again we do not know how this might occur, Gli protein regulation is a likely target for regulation of the Hh pathway given that Gli function can be modulated by other pathways in a variety of other contexts (Aberger and Ruiz i Altaba, 2014).

Despite our results showing limited transcriptional cross-regulation between Shh and Fgf signalling during NT patterning of the optic vesicle, these pathways show many such regulatory interactions in other contexts. For example, Shh promotes fgf8 expression in the rostral-most tip of the prosencephalon, and Fgf in turn promotes basal telencephalic Shh expression in a cross-regulatory interaction that modulates telencephalic patterning (Aoto et al., 2002; Danesin et al., 2009; Ohkubo et al., 2002; Shannagalingam et al., 2000; Shinaya et al., 2001; Storm et al., 2006; Walshe and Mason, 2003; this study). Similarly in cavefish, enhanced levels of shh expression at neural plate stages is correlated with precocious and stronger expression of fgf8 in the prospective telencephalon (Menent et al., 2007; Pottin et al., 2011). In the limb, Shh (expressed in the posterior portion of the primordium, known as the zone of polarising activity) and Fgfs (expressed in the distal portion of the limb primordium, termed the apical ectodermal ridge) engage in a complex regulatory feedback loop essential for allocation of correct proportions to elements in the growing limb (reviewed by Benazet et al., 2009; Benazet and Zeller, 2009; Scherz et al., 2004; Zuniga et al., 1999). In the ventral CNS, coordinated Fgf and Shh activities regulate the generation of cell diversity (Sasai et al., 2014). In this context, spatiotemporal
following manipulations of Fgf and Hh signals. The implications below are based on the ability of Foxg1 to repress foxg1 expression but is not required for repression of foxd1 expression. (i) Shh gain of function: loss of foxg1 expression and gain of foxd1 in nasal retina. This implies that Shh signalling promotes foxd1 expression and/or inhibits foxg1 expression. Blue shading and dots represent Shh expression. (ii) Shh loss of function: loss of foxd1 in temporal retina. This implies that Shh promotes foxd1 expression and is not required for repression of foxg1. (iii) Combined loss of Shh and Fgf: loss of foxg1 and gain of foxd1 in nasal retina. This implies that either unknown signals (grey arrow in B) promote foxd1 expression in absence of Shh or that repressors (such as Fgf itself) are removed in this situation. The result also implies that Fgf is required for the repression of foxd1 in temporal retina (shown in ii), and that this repression is independent of Foxg1 (which is not expressed in temporal retina). (iv) Loss of Fgf expression: loss of foxg1 and gain of foxd1 in nasal retina. This implies that Fgf promotes foxg1 and/or inhibits foxd1 expression. (v) Gain of Fgf function: gain of foxg1 expression and loss of foxd1 expression in temporal retina (data taken from Picker and Brand, 2005; Picker et al., 2009). This implies that Fgf promotes foxg1 expression and/or inhibits foxd1 expression. (B) Proposed regulatory interactions that could explain the coincident expression of Foxg1 and Foxd1 in the nasal retina. This implies that Fgf promotes development of pax2+ ventral retina identity in the nasal retina. As stated in the main text, the regulatory interactions leading to nasotemporal patterning occur from neural plate stage onwards. (C,D) Images showing the domains of expression in the forebrain of genes encoding the signals studied (C) and their Fox gene targets (D), as evident from double in situ hybridisation assays of 10ss embryos. Dashed lines outline the optic vesicles.

Eye field cells extensively intercalate among each other as they incorporate in the evaginating primordia (Ivanovitch et al., 2013). We have speculated that this mixing means that it is not possible to predict the final fate of many cells within the eye field and, consequently, we have proposed that regional fate would only be established after cells have evaginated into the optic vesicles. The results shown in this study show that signals influencing NT patterning are acting from very early stages, probably prior to completion of the integration of eye field cells into the optic vesicles. However, the signals required to establish NT pattern are produced and secreted by dorsal and ventral forebrain territories with organiser-like properties (Picker et al., 2009). These territories constitute ‘fixed’ domains relative to the eye field/optic vesicle, and exert their influence upon cells entering either the dorsal or the ventral half of the eye primordium, irrespective of their original location within the eye field prior to evagination. This mechanism of fixing the sources of signals could provide robustness to patterning in morphogenetic contexts where cells are undergoing dynamic reorganisations.

Generating sharp boundaries downstream of morphogenetic signals
In the spinal cord, Shh controls the expression of transcription factors that collectively subdivide the neural tube into discrete generative domains along its DV axis (reviewed by Dessaud et al., 2008). Shh-regulated transcription factor-encoding genes expressed in adjacent domains are frequently cross-repressive. This has the consequence that any individual cell (usually at a boundary between domains) would resolve its expression to one or other of the mutually repressive genes, thereby sharpening the boundary between domains (Cohen et al., 2013). The scenario we describe in the optic vesicle is highly reminiscent of this mode of patterning.
Shh initiates expression of foxd1, and then Foxd1 represses foxg1, which is induced by Fgfs and, in turn, Foxg1 can repress foxd1. This cross-repression would then ensure that the cells at the NT boundary would only adopt either nasal or temporal identity. In this way, the early graded activity of Shh and Fgf could be translated into the establishment of a sharp NT border that is maintained throughout later stages of eye development.

**MATERIALS AND METHODS**

**Fish lines and husbandry**

AB and tupl wild-type zebrafish strains, and transgenic lines Tg[rx3::GFP];fli1::dsRed (Brown et al., 2010; Rembold et al., 2006), Tg[emx3::YFP];fli1::dsRed (Viktor et al., 2009), Tg[rx3::Gal4-VP16];fli1::dsRed (Burger et al., 2012), Tg[ptch2::kaede];fli1::dsRed (Huang et al., 2012), Tg[fxn::lacZ];fli1::dsRed (Chen et al., 2009), Tg[Hcn4::GFP];fli1::dsRed (Piecer et al., 2009) were maintained and bred according to standard procedures (Westerfield, 1993). Laboratory stocks of A. mexicanus surface fish and cavefish (Pachón population) were obtained from the Yamamoto laboratory at UCL. All experiments conform to the guidelines from the European Community Directive and the British and Spanish legislation for the experimental use of animals.

**Microinjection and drug treatments**

shh, foxd1 and foxg1 were expressed in the optic vesicles using the UAS/Gal4 system (Halpern et al., 2008). UAS constructs were generated by subcloning the test cDNA into a bidirectional UAS/toI2 plasmid, which drives GFP transcription in one direction and the test cDNA transcription in the other (Distel et al., 2010; Kajita et al., 2014). UAS constructs were injected into one-cell-stage Tg[rx3::Gal4]; embryos (at 20–40 pg/embryo) and the embryos showing homogenous GFP expression in the eye primordia were selected for further analysis. shh mRNA for microinjection was synthesised using the mMessage Machine kit (Ambion), following the manufacturer’s instructions.

Drug treatments were performed by incubating dechorionated embryos in E3 medium with cyclopamine (100 μM, Calbiochem), SU5402 (10 μM, Calbiochem) or a combination of both. As stocks of cyclopamine and SU5402 were kept in DMSO, controls for these treatments were incubated in the same amount of E3 medium with the equivalent concentration of DMSO. The treatment was stopped at 10/12ss and the embryos were washed and fixed for further analysis. Note that in our experimental conditions, Shh/Fgf abrogations are performed once the first stages of forebrain patterning have taken place, and thus are unlikely to promote changes in primary forebrain subdivisions, as revealed by the normal expression of optic vesicle and telencephalic markers (Fig. S2C–H; see also Rohr et al., 2001; Shinya et al., 2001).

**mRNA detection and immunolabelling**

Antisense mRNA probes for whole-mount in situ hybridisation were synthesised using RNA polymerases (Promega) and digoxigenin- or fluorescein-labelled nucleotides (Roche), following the manufacturer’s instructions. Whole-mount in situ hybridisations were performed essentially as previously described (Cavodeassi et al., 2013; Yamamoto et al., 2004). For visualisation, embryos were incubated with anti-digoxigenin- or fluorescein-AP or fluorescein-AP and developed using NBT/BCIP substrates (Roche). For fluorescent detection, embryos were incubated with anti-digoxigenin-POD (Roche) and developed using Cy3-TSA (Perkin Elmer) as a substrate. Immunolabelling was performed as previously described (Cavodeassi et al., 2013) with the following antibodies: chicken anti-GFP (Abcam, cat. no. ab13970; 1:1000); mouse anti-β-casein (Signal Transduction Laboratories, cat. no. 610154; 1:400) and Alexa-488 and -647 coupled secondary antibodies (Jackson ImmunoResearch, 1:500). Sytox Orange (Life Technologies, 1:10,000) was used to counterstain nuclei.

**Tracing of retinotectal projections**

Dil and DiO were used to label nasal and temporal retinal ganglion cells at 6 dpf in paraformaldehyde-fixed wild-type and Tg[rx3::Gal4]; UAS-Shh retina. Fries were incubated at room temperature for 24 h before preparing them for imaging. Each tectum and its corresponding eye were sequentially imaged.

**Imaging and data processing**

Dil/DiO-traced embryos and Tg[ptch2::kaede];fli1::dsRed embryos were embedded in low melting point agarose (Sigma) at 1-1.5% in PBS for confocal imaging using a 40× (0.8NA) long-working distance water immersion lens. A Zeiss LSM710 confocal microscopy system was used for image acquisition.

In situ hybridised embryos were mounted flat in a drop of glycerol and dorsal images were acquired with a 20× (0.70NA) dry lens using a Leica CTR 5000 microscope connected to a digital camera (Leica DFC 500), and operated by Leica software. Some of these embryos were embedded in gelatine/BSA for vibratome sectioning as previously described (Sanchez-Arrones et al., 2013). Sections (20 μm thick) were obtained using a Leica VT1000S vibratome, mounted in glycerol, and imaged with a 40× (0.85NA) dry lens.

Raw confocal data were analysed with Fiji/ImageJ. Images were exported as TIFF files and all figures were composed using Photoshop.

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**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**

While working with M.B., A.P. made observations that led F.C. and G.G. to conceive and design the study with input from S.W.W. and P.B.; M.-H.-B., G.G., F.C. and L.S. performed experiments; F.N. (P.B.’s lab) and M.T. helped prepare molecular biology tools; S.W.W., G.G. and F.C. wrote the manuscript; all authors read and approved the manuscript.

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**Supplementary information**

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