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Dissecting the role of Wnt signaling and its interactions with FGF signaling during midbrain neurogenesis

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Keywords: axin, GSK-3, IWR-1, mesencephalon, neuron, trigeminal, Tankyrase, zebrafish, β-catenin

Abbreviations: MTN, mesencephalic trigeminal nucleus; nTPC, nucleus of the tract of the posterior commissure; Wnt, wingless related integrated site; FGF, Fibroblast growth factor; CA-fgfr1, constitutively active fgf receptor 1; BIO, 6-bromoindirubin-3'-oxime; IWR-1, Inhibitors of Wnt Response 1; cat, β-catenin; dkk1, dickkopf Wnt signaling pathway inhibitor 1; GSK-3, glycogen synthase kinase; A-P, anterior-posterior; GFP, green fluorescent protein; hpf, hours post fertilization; dpf, days post fertilization.

Interactions between FGF and Wnt/β-catenin signaling control development of the midbrain. The nature of this interaction and how these regulate patterning, growth and differentiation is less clear, as it has not been possible to temporally dissect the effects of one pathway relative to the other. We have employed pharmacological and genetic tools to probe the temporal and spatial roles of FGF and Wnt in controlling the specification of early midbrain neurons. We identify a β-catenin (βcat) independent role for GSK-3 in modulating FGF activity and hence neuronal patterning. This function is complicated by an overlap with βcat-dependent regulation of FGF signaling, through the regulation of sprouty4. Additionally we reveal how attenuation of Axin protein function can promote fluctuating levels of βcat activity that are dependent on FGF activity. This highlights the complex nature of the interactions between FGF and Wnt/β-catenin and reveals that they act at multiple levels to control each others activity in the midbrain.

Introduction

The control of neurogenesis is critical for ensuring the correct number of neurons form at the appropriate place during development and regeneration. Disruption to this process occurs in a number of congenital disorders that result in cognitive impairment.¹ Signaling pathways play a critical role in controlling where and when neurons form, and so are presumed to be robustly regulated, to ensure that fluctuations of any one pathway are buffered and do not perturb neurogenesis. Buffering of signaling pathway activity is achieved through regulatory interactions between pathways, that act to limit or promote activity, for instance by controlling expression of ligands or the activity of activators or repressors. The interaction between Wnt and FGF signaling in the developing midbrain is a well-explored example of this interplay between 2 critical pathways.²,³

FGF and Wnt Regulation of Neurogenesis

The isthmus arises at the midbrain-hindbrain boundary and acts as an organizer for adjacent tissues.³,⁴ In the midbrain, FGFs secreted from the isthmus controls the patterning of the midbrain and anterior hindbrain.⁵-¹⁰ At later stages, FGF activity controls the onset of neurogenic differentiation across the midbrain¹¹,¹² and acts to specify dopaminergic and serotonergic neurons in the ventral midbrain.¹³-¹⁵ Changes to midbrain identify in animals showing reduced levels of FGF signaling are presumed to reflect a key role of FGFs in specifying regional fate in the midbrain. Specifically, mice or zebrafish with loss of function of Fgf8 show hyoplastic midbrain and anterior hindbrain.¹⁶,¹⁷

The canonical Wnt signaling pathway activates the nuclear transcription co-factor β-catenin (βcat) and is important for multiple aspects of neuronal development. It is known to be important for regulating cell proliferation through the cell cycle regulator cyclinD1 and c-myc and perturbations to Wnt affect midbrain size.¹⁸-²³ Wnt/βcat signaling is also a regulator of neurogenesis and induces expression of Neurogenin1, Neurogenenin2 and NeuroD1.²⁴,²⁵ Both early specification and later differentiation of dopaminergic neurons in the ventral midbrain are regulated by Wnt/β-catenin signaling.²⁶-³⁰

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Cross-Talk between Wnt and FGF

A well-characterized regulatory feedback loop operates to maintain Wnt1 and Fgf8 expression at the isthmus.2 Manipulations of Wnt or FGF signaling in chick embryos have revealed that both pathways are required for activity of the other.31 However, it is unclear if there is a hierarchy of events in which one pathway controls the others and whether they alter the biological responses of each other. Computational modeling of the spatial expression of Wnt and FGF signaling pathway genes in mutant mice has suggested that FGF signaling is required for the maintenance of Wnt1 expression at the isthmus, but not induction.32 A number of studies reveal that Wnts and FGFs have multiple roles during midbrain development and neurogenesis, independent of their role in conferring regional patterning. In cortical neurons, bcat acts to promote neuronal differentiation and can override FGF signals that promote proliferation, by inducing expression of the pro-neurogenic factor Neurogenin1.24 Neural stem cells likewise respond differently to Wnt and FGF signaling dependent on whether both signals are present. In the presence of FGF2, bcat promotes neural stem cell proliferation; in an absence of FGF2 bcat promotes neuronal differentiation.33 Thus an interplay between Wnt and FGF regulates both neuronal progenitor proliferation, but also differentiation. The balance of these respective roles is therefore critical for orchestrating growth of the developing brain and ensuring that appropriate neuronal populations form in the correct sites.

We have previously investigated how development of early forming dorsal brain neurons are regulated by FGF and Wnt signaling.34 Using a combination of pharmacological and genetic manipulations we found that positioning and number of mesencephalic trigeminal nucleus (MTN) neurons is dependent on the level of FGF and Wnt activity. We and others have shown that FGF signaling from the isthmus controls neuronal differentiation in the midbrain, through regulation of Hairy-related genes her5 and hins.8,35,36 A posterior retraction of her5 expression toward the isthmus controls where and when neuronal differentiation occurs in the midbrain.37 Using pea3 as a readout of FGF activity, we postulated this corresponds to a gradient of FGF signaling that is retracting posteriorly in the midbrain during development.34 We investigated the interaction of FGF and Wnt in controlling this process by applying inhibitors of FGF receptors (SU5402 and GSK-3) and SU5402 and GSK-3 (BIO). This revealed that FGF signaling is GSK-3 dependent and that the FGF receptor inhibitor sprouty4 is regulated by Wnt signaling. It is important to understand the nature of these interactions because of their potential impact on the spatiotemporal control of neurogenesis in the brain. We have therefore investigated the role of Wnt/bcat activity in controlling development of MTN neurons in the midbrain and how the interaction with FGF signaling affects this process.

In this work, we identify an interaction between GSK-3 and FGF intracellular signaling pathways, independent of the Wnt/bcat pathway. Specifically we note that attenuation of Wnt/bcat signaling or of Axin function do not alter positioning of MTN neurons, in contrast to an inhibition of GSK-3 function. Furthermore, FGF responsive genes are affected differently by bcat overexpression and manipulation of GSK-3. Intriguingly, we find that bcat-regulated genes do not respond in a linear manner to Axin protein levels, suggesting that feedback loops act to modulate the output of Wnt/bcat during midbrain development.

Methods

Animals and embryo manipulations

All experiments were performed in accordance with UK Home Office regulations. Embryos were grown at 28.5°C as previously described.38 Lines used were AB (considered to be wild-type), masterblind (mbl),39 Tg[elavl3:gfp],40 Tg[dusp6:d2eGFP],41 Tg[hsps70:dkk1b-gfp],42 Tg[hsps70:ca-fgg-1],43 Tg[hsps70:gal4],44 Tg[dlc5a6a:gfpGFP],45 Tg[UAS:HA-B-catenin],46 Tg[TOP4GFP].46

Heat shock induction was performed by moving embryos to 37°C for 2 hours at 16.5 hours post fertilization (hpf). Pharmacological treatments were performed by applying either SU5402 (Sigma), BIO (Invitrogen) or IWR-1 (Merck) diluted in embryo medium as previously described.34 For all experimental conditions, a minimum of n = 10 embryos were used; for each individual experiment containing multiple conditions, embryos from the same clutch were used to minimise variation in developmental stage.

In situ hybridization and Immunohistochemistry

Gene expression was visualised by in situ hybridization and proteins detected by immunohistochemistry as previously described.47,48 Antibodies used were anti-HuC/D (1 : 500, Invitrogen), anti-Isl1 (1 : 200, DSHB), anti-acetylated tubulin (1 : 200, Sigma), anti-GFP (1 : 500, AMS Biotechnology), anti-HA (1 : 300, Roche). Back labeling of axons was performed by applying DiI or DiD to muscles of fixed 5 dpf larvae using a sharpened tungsten needle. Fluorescent images were acquired using a Nikon C-1 Eclipse confocal microscope and processed using Photoshop (Adobe).

Mathematical modeling

Statistical models and analyses were generated using the R programming language (R Development Core Team, 2010) as described previously.34 A minimum of 10 measurements were used for each condition in each experiment. The models used tested variables across a number of datasets and assessed batch effects for significance.

The model of Lee et al.49,50 describing Wnt signaling and bcat activity was converted into equivalent code for the Python programming language. Under the assumption that degradation of Axin (reaction 15 in the original model, described by the rate constant k15) is primarily through its ubiquitination by Tankyrase, this model was then simulated under varying values of k15 (other rates were kept as in the original model description).
Results

FGF signaling controls positioning and number or early forming midbrain neurons

We have previously identified MTN neurons in the anterior midbrain by retrograde labeling of adductor mandibulae muscles using DiI.\(^3^4\) In order to ascertain whether MTN neurons also innervate other cranial muscles, we labeled lateral rectus and levator arcus palatini muscles with DiD and adductor mandibulae muscle with DiI in 5 day post fertilization (dpf) larvae. We found that MTN neurons were back labeled with both DiD and DiI, but all labeled MTN neurons were restricted to the anterior midbrain, as we have found previously (Fig. 1A). To understand why MTN neurons arise in the anterior midbrain, we used a transgenic line that labels developing neurons in the developing brain. The elavl3 gene encodes the HuC protein, a marker of differentiated neurons.\(^4^0\) At 24 hpf, GFP expressing (GFP+) neurons in Tg[elavl3:eGFP] embryos are observed in the dorsal brain, in the nucleus of the posterior commissure (nTPC) and in the anterior midbrain. GFP+ MTN neurons undergo differentiation in an anterior-posterior manner from 22 hpf as shown by the presence of HuC protein (Fig. 1B). Treatment with the FGF receptor antagonist, SU5402, at stages prior to MTN differentiation, leads to an increased number of MTN neurons that lie at more posterior positions along the midbrain, relative to control animals (Fig. 1C).\(^3^4\) This suggests that FGF signaling controls where MTN neurons will form in the midbrain during development. Isl1 is expressed by all primary neurons in the developing zebrafish brain.\(^5^1\) To determine whether FGF signaling is active in the anterior midbrain where MTN neurons will first differentiate, we labeled MTN neurons by an anti-Isl1 antibody and compared to GFP localization in a reporter line for FGF signaling that expresses GFP under the control of the Dusp6 promoter (Tg[dusp6:d2GFP]). Strikingly, there was no co-localization of GFP and Isl1 revealing that MTN neurons differentiate in regions devoid of FGF signaling (Fig. 1D–I). Commensurate with this, fgf8a is not expressed in anterior midbrain cells at this stage, suggesting that cells are not able to respond to FGF signaling (Fig. 1J). We wished to know whether a temporal inhibition of FGF signaling during stages prior to MTN formation would affect the development of later-forming neuronal populations in the midbrain including the optic tectum. To investigate this, embryos were treated from 14–24 hpf with SU5402 or DMSO, then drug washed away and embryos allowed to develop until 30 hpf. In SU5402 treated embryos we observed more posteriorly located MTN neurons in the midbrain and a smaller optic tectum (Fig. 1K and L). Thus, a temporal inhibition of FGF signaling at stages when primary neurons form, leads to perturbations of midbrain neuronal architecture.

Wnt/βcat signaling interacts with FGF to direct MTN formation

The well documented interaction between FGF and Wnt/βcat signaling suggests that manipulations of βcat activity would also affect positioning of MTN neurons. We therefore compared how alterations of Wnt relative to FGF signaling affected the positioning of MTN neurons. MTN neuron positioning relative to the isthmus was quantified in 24 hpf embryos under the following conditions: 1) expression of a constitutively active FGF receptor (CA-Fgfr1), 2) application of SU5402, 3) expression of the Wnt antagonist dickkopf1b (dkk1), 4) application with BIO. All manipulations were performed between 14–24 hpf (SU5402, BIO) or 16.5–24 hpf (CA-Fgfr1, dkk1) as we have previously shown that MTN, but not adjacent diencephalic neurons, are sensitive to manipulations of FGF and Wnt signaling at this stage.\(^3^4\) The position of the most posteriorly located MTN neurons in the midbrain was measured relative to the isthmus for each condition and expressed as a ratio relative to the midbrain size to compensate for any differences in size. This revealed that over-activation of FGF resulted in an anterior shift of MTN neurons (Fig. 2A). In contrast, SU5402 treated embryos displayed posteriorly located MTN neurons relative to controls (Fig. 2B). BIO treatment caused a similar phenotype to SU5402 treatment, with MTN neurons present at more posterior positions in the midbrain (Fig. 2C). In contrast, abrogation of Wnt signaling by overexpression of dkk1 had no effect on MTN positioning (Fig. 2D). This suggests that the posterior displacement of MTN neurons observed in BIO treated embryos may reflect a role for GSK-3 in controlling neuronal differentiation along the dorsal midbrain, independent of its role in regulating Wnt signaling.

GSK3 and βcat differentially regulate FGF signaling in the midbrain

The different changes to neuronal patterning caused by altering Wnt and FGF activity suggests that they do not interact in a simple feedback loop to control neurogenesis in the midbrain. To understand the importance of GSK-3 in mediating interactions between Wnt and FGF, we compared the responses of FGF signaling genes to alterations of GSK-3 and βcat activity. Previously, we showed that BIO treatment up-regulates fgf8a expression at the isthmus. To determine whether FGF-dependent genes such as fgf8a are regulated by GSK-3 or βcat activity, the effects of GSK-3 inhibition or βcat over-expression were compared when FGF signaling was attenuated using the inhibitor SU5402. Embryos were treated with 10μM SU5402 from 14 hpf in the presence of varying doses of BIO or a stabilised HA tagged βcat. Expression of fgf8a at the isthmus was assessed at 24 hpf by in situ hybridization and found to be down-regulated by SU5402 treatment (Fig. 3A and B). In contrast, BIO causes elevated fgf8a expression compared to controls (Fig. 3C). Surprisingly, in the presence of both BIO and SU5402, fgf8a expression was higher than in embryos treated with BIO alone (Fig. 3D). Overexpression of βcat resulted in reduced fgf8a expression, unlike BIO treatment (Fig. 3E and F). In the presence of SU5402, overexpression of βcat then rescued fgf8a relative to embryos treated with SU5402 alone (Fig. 3G and H). These results were consistent between embryos (see also Fig. S1) and reveal that fgf8a responds differently to BIO treatment and βcat overexpression. However, both BIO and βcat over-expression are able to rescue fgf8a expression in the presence of SU5402.

To show how fgf8a responses compare to a transcriptional read-out of FGF activity we assessed the response of the ETS
Figure 1. For figure legend, see page 5.
family gene pea3 at the isthmus and midbrain signaling under different levels of FGF, GSK-3 and bcat activity. Both SU5402 and BIO treatment cause a reduction of pea3 expression (Fig. 3L). SU5402 was used at 6μM in combination with BIO as higher SU5402 concentrations (10μM) lead to a loss of pea3 expression, precluding quantification. In the presence of SU5402, BIO caused a further reduction of pea3 expression than when treated with BIO or SU5402 alone (Fig. 3L).

Overexpression of bcat also leads to a reduction of pea3 expression, similar to BIO (Fig. 3M and N). In contrast to BIO, over-expression of bcat in the presence of SU5402 does not further repress pea3 (Fig. 3O, see also Fig. S2). These differential responses of genes in the FGF signaling pathway to BIO and bcat overexpression suggests that GSK-3 affects FGF signaling in a bcat-independent manner (Table 1).

**Wnt responsive genes are affected differently by changes to b-catenin and GSK-3 activity**

GSK-3 may also regulate Wnt signaling independently of its role in inhibiting b-catenin activity in the bcat destruction complex (bcatDC). To test this we investigated how genes in the Wnt pathway are affected by inhibiting FGF signaling in conjunction with GSK-3 inhibition compared to bcat overexpression. Application of SU5402 or BIO leads to reduced wnt1 expression (Fig. 4A–C). Application of BIO in presence of SU5402 causes a further inhibition of wnt1 (Fig. 4D). In contrast to the response of wnt1 to BIO treatment, wnt1 is up-regulated by overexpression of bcat (Fig. 4E and F). Application of SU5402 abrogates this response (Fig. 4G and H, see also Fig. S3). This reveals a differential response of wnt1 to inhibition of GSK-3 and elevated b-catenin activity, suggesting that GSK-3 has a bcat-independent function in controlling wnt1 expression.

To determine how GSK-3 inhibition or bcat over-expression can affect Wnt/ bcat activity, we used left as a transcriptional readout. SU5402 treatment results in down-regulation of left (Fig. 4I and J). In contrast, inhibition of GSK-3 by BIO results in a slight up-regulation of left expression (Fig. 4K). In the presence of SU5402 and BIO, left expression was strongly upregulated (Fig. 4L). This upregulation was much greater than in embryos treated with BIO alone, implying that GSK-3 inhibition causes a much stronger activation of bcat when FGF signaling is likewise inhibited. We then evaluated how overexpression of bcat affects left expression. As predicted, bcat over-expression causes an up-regulation of left (Fig. 4M and N). In the presence of SU5402, bcat overexpression can rescue left expression (Fig. 4O and P, see also Fig. S4).

In summary, we found that left expression is reduced by SU5402, indicating a requirement for FGF activity to promote bcat signaling. Both BIO and bcat can rescue this reduction in the presence of SU5402, suggesting bcat regulation of left is not dependent on FGF activity.

**Inhibition of Wnt signaling does not affect MTN neuron positioning in the midbrain**

To further probe the relative roles of Wnt and FGF signaling in controlling each others activity, we focused on the role of the key regulator of the bcat destruction complex, Axin. We have previously described how IWR-1 acts in an antagonistic manner to SU5402 to control the number of MTN neurons that form. Inhibition of Wnt signaling (by over-expression of dkk1) does not affect MTN positioning (Fig. 2D). We therefore tested whether stabilization of Axin, through inhibition of Tankyrase, would affect MTN positioning in the midbrain. Although application of varying IWR-1 doses resulted in the formation of fewer MTN neurons (Fig. 5A) there was no effect on the distance of MTN neurons to the isthmus (Fig. 5B). A comparison of MTN neuron number relative to the MTN-isthmus distance showed no correlation when embryos were exposed to IWR-1 in the presence of SU5402 (Fig. 5C). We then asked whether changes to the MTN-isthmus distance in embryos exposed to IWR-1 and SU5402 could be explained by the application of either IWR-1 or SU5402. We find that there is no correlation between MTN neuron number and distance to the isthmus in embryos exposed to both IWR-1 and SU5402 (R = 0.028, Fig. 5D). Two-way ANOVA tests revealed that IWR-1 had no significant affect (p = 0.616) on MTN neuron positioning, but SU5402 had a strong affect (p = 0.0012). Moreover, there is no interaction effect expected if IWR-1 and SU5402 are acting synergistically or antagonistically (p = 0.839). In contrast, models that describe MTN neuron number revealed that there is both a strong IWR-1 affect (p = 1.23 × 10⁻¹⁰, Table 2) and a strong interaction effect between IWR-1 and SU5402 (p = 0.0048, Table 2). These models indicate that although inhibition of Tankyrase results in fewer MTN neurons, this does not occur in conjunction with posterior shifts of MTN neurons observed following abrogation of FGF activity (by SU5402) or inhibition of GSK-3 (by BIO). Loss of Wnt signaling by overexpression of dkk1 likewise causes a decrease in the number of MTN neurons forming, but this does not correlate with altered positioning within the midbrain.

**Figure 1 (See previous page).** FGF signaling dictates the spatial positioning of MTN neurons in the midbrain during development. Dil (red) labeling of masseter and and DiD (blue) labeling of levator arcus palatini and lateral rectus cranial muscles in 5 dpf larvae leads to retrograde labeling of MTN neurons in the anterior midbrain (A). Lateral views of Tg(elavl3:eGFP) embryos labeled with anti-GFP (green) and anti-Elavl3 (Huc/D, red) reveals the presence of more MTN neurons (arrowheads) at posterior locations in the midbrain following treatment with 40μM SU5402 from 14–24 hpf (C) relative to DMSO exposure (B). Bracket indicates extent of MTN neurons (represented by enlarged area in B and C). Dorsal (D–F) and lateral (G–I) views of 24 hpf Tg (dusp6d2eGFP) embryos processed with anti-GFP (green) and anti-Is1 (red). A zoomed dorsal view (F') reveals that neurons of the nucleus of the tract of the posterior commissure (nTPC, asterisk) and MTN neurons (arrowheads) develop in regions devoid of anti-GFP labeling. At 24 hpf, fgfr1 expression is absent from the anterior midbrain (J). Lateral views of 30 hpf Tg(dlk5a:6acGFP) embryos labeled with anti-Elavl3 (red), anti-acetylated tubulin (blue) and anti-GFP (green) reveals more MTN neurons (arrowheads) and a reduced optic tectum (bracelet) following exposure to 40μM SU5402 (L) from 14–24 hpf compared to DMSO treated control animals (K). Nucleus of the posterior commissure (nPC), trochlear nerve (nIV). Scale bars: 50μm (A), 100μm (B–L).
This suggests that inhibition of Wnt signaling by either dkk1 over-expression or IWR-1 application does not perturb the positioning of MTN neurons.

The Hairy-related gene her5 controls the spatiotemporal onset of neurogenesis in the midbrain and hence where MTN neurons form.8,35 The expression of her5 along the A-P extent of the dorsal midbrain is controlled by GSK-3 and FGF activity.34 To determine whether her5 shows differential responses to IWR-1 over time, we measured the spatial expression of her5 at 16.5, 18 and 20 hpf after application of IWR-1 at 14 hpf. We found that no significant changes to her5 expression occurred initially after exposure to IWR-1, although by 18 hpf the her5 expression was

![Figure 2. MTN A-P positioning along the dorsal midbrain is regulated by FGF and GSK-3 activity, but does not require Wnt signaling. Box plots representing the minimal distance between MTN neurons and the isthmus scaled relative to midbrain size for embryos expressing CA-fgfr1 (A), exposed to 0 or 40µM SU5402 (B), exposed with 0, 1, 2, 4µM BIO (C), or expressing dkk1b (D). Significance was determined by t-test with Welch correction (A, B, D) or by a Kruksal-Wallis test (C) by comparing to embryos not expressing transgenes or treated only with DMSO carrier (0µM). N = 10 for each condition.](image)
reduced relative to control embryos (Fig. 5F–J). However, by 24 hpf, there no longer an effect of IWR-1 treatment on her5 expression in the midbrain.

Having shown that her5 is not significantly affected by IWR-1, we then tested if inhibition of Wnt signaling would affect the response of her5 to FGF activity. IWR-1 and SU5402 were applied simultaneously at 14 hpf and the spatial expression of her5 measured along the dorsal midbrain at 24 hpf. Plots of her5 expression revealed that IWR-1 did not alter the response of her5 to SU5402 (Fig. 5K). We confirmed this by generating models for the response of her5 to IWR-1 and SU5402 (Table 3). These revealed that application of IWR-1 did not have a significant affect on her5 (p = 0.322). In contrast, SU5402 had a significant effect (p = 0.000282). Furthermore, IWR-1 did not significantly alter the response of her5 to SU5402 (p = 0.0763). This reveals that bcat activity is not required for the response of her5 to FGF activity and so does not control the A-P position of MTN neurons in the dorsal midbrain, unlike GSK-3.

bcat activity responses to IWR-1 are not linear relative to dose or time of exposure

Our observation that IWR-1 application caused a transient decrease in her5 expression led us to wonder whether it caused repression of bcat activity in a dose-dependent and uniform manner. We therefore used expression of lef1 in the midbrain as a readout of bcat activation and compared embryos treated with IWR-1 at varying doses (20, 30, 40 M) from 14 hpf after 2.5 (16.5 hpf), 4 (18 hpf) and 6 (20 hpf) hours of exposure. Intriguingly, we found that lef1 responses were affected more by application of 20 M IWR-1 than either 30 or 40 M after 2.5 hours post application (Fig. 6A–D). At later stages this changes, until by 12 hours post application lef1 is most strongly reduced in embryos treated with the higher doses of 30 and 40 M (Fig. 6E–L). Why lef1 should be more affected by a lower, rather than higher dose of IWR-1 initially is unclear. Expression of wnt1 at the isthmus is responsive to BIO and bcat activity.
We found that the lowest dose of IWR-1 tested (10 μM), resulted in the strongest downregulation of wnt1 expression (Fig. 6M–P). We then turned to an alternative reporter of Wnt/b-catenin activity, the Tg[TOPdGFP] transgenic line, to determine if these responses of lef1 represent Wnt activity. In this transgenic line, we were unable to discriminate any differences in b-catenin activity when treated at different IWR-1 doses (Table 1, data not shown). This may reflect the relative insensitivity to changes in Wnt signaling levels previously reported.52 We therefore examined other readouts of b-catenin activity to determine how they responded to different concentrations of IWR-1 over time.

Previously, we found that the FGF receptor inhibitor, sprouty4 (spry4) shows a dual response to FGF and Wnt/GSK-3 activity in the midbrain.34 Strikingly, we noted that spry4 is sensitive to the level of b-catenin activity independently from FGF activity. We therefore measured the response of spry4 to varying doses of IWR-1 from 14 hpf, to determine how similar its response was to that of lef1. As observed for lef1, expression of spry4 was reduced expression relative to control when over-expressing b-catenin (F, N), when over-expressing b-catenin and treated with SU5402 (H, P). Isthmus (i). Scale bars: 100 μm.

**Table 1.** Summary of gene expression changes in the midbrain at 24 hpf due to alterations of Wnt or FGF activity from 14 hpf (SU5402, IWR-1, BIO) or 16.5 hpf (dkk1, β-catenin).

<table>
<thead>
<tr>
<th>Signaling pathway manipulation</th>
<th>gene expression in the midbrain</th>
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<tbody>
<tr>
<td>Wnt</td>
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<td>↑</td>
<td>BIO</td>
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reduced expression relative to control

no change relative to control

elevated expression relative to control

**Figure 4.** wnt1 in the midbrain is GSK-3 dependent, but is not regulated by β-catenin. Expression of wnt1 (A–H) and lef1 (I–P) was visualised by in situ hybridization in 24 hpf embryos treated with DMSO (A, E, I, M), SU5402 at 10 μM (B, G, J, O), BIO at 4 μM (C, K), SU5402 and BIO together (D, L), when over-expressing b-catenin (F, N), when over-expressing b-catenin and treated with SU5402 (H, P). Isthmus (i). Scale bars: 100 μm.
Figure 5. For figure legend, see page 11.
A model of Axin inhibition predicts oscillating bcat activity

We found that Wnt/ bcat responsive genes left1 and spry4 show a non-linear response to IWR-1 and this changes relative to the duration of exposure. One putative explanation for the differential effects of IWR-1 dosage on Wnt-target genes may therefore be due to feedback from FGF signaling to promote elevated bcat signaling. IWR-1 inhibition of Tnk reduces the rate of Axin protein degradation, a key limiting step in the activation of bcat.53,54

Table 2. Results from Poisson models describing MTN neuron numbers as a function of SU5402 at 10 μM ([SU5402]10) and IWR-1 at 20 μM ([IWR1]20), 30 μM ([IWR1]30), or 40 μM ([IWR1]40) and SU5402 at either 20 or 30 μM ([SU5402]20, [SU5402]30). The baseline number of MTN neurons is represented by μ and interactions represented by δ. Addition of IWR-1 at 20 or 30 μM results in significant changes to MTN neuron number (p < 0.001), but SU5402 at 10 μM does not (p > 0.05). In the presence of both SU5402 and IWR-1 results in significant changes to MTN neuron numbers that cannot be explained by simply additive effects, but rather represent interaction effects e.g. δ([IWR1]30) · δ([SU5402]30) · δ([IWR1] · [SU5402]20 & 30).

| Estimate Std. Error | z value | Pr(>|z|) |
|----------------------|---------|----------|
| (Intercept)           | 1.9617  | 0.1250   | 15.693  | < 2e-16 |
| [IWR1]20              | -0.7916 | 0.2238   | -3.536  | 0.000406|
| [IWR1]30              | -1.2197 | 0.2515   | -4.850  | 1.23e-06|
| [SU5402]20            | 0.1316  | 0.1712   | 0.768   | 0.442269|
| [SU5402]30            | 0.5066  | 0.2832   | 1.789   | 0.073613|
| [SU5402]20 · [IWR1]   | 0.3074  | 0.0374   | 8.222   | < 2e-16 |

Table 3. Results from generalized linear models describing expression of her5 (scaled relative to midbrain size) as i) a function of SU5402 at 10 μM ([SU5402]10) and IWR-1 at either 20 or 30 μM ([IWR1]20, [IWR1]30), or ii) a function of SU5402 at 10 μM relative to IWR-1 ([IWR1]). Addition of IWR-1 at 20 or 30 μM does not result in significant changes to her5 expression (p > 0.05), but SU5402 does (p < 0.001). Addition of 30 μM IWR-1 in the presence of SU5402 has an effect on her5 expression with low significance (p < 0.1), but overall IWR-1 does not significantly alter the response of her5 to SU5402 (p = 0.076). Fit of data to models R² = 0.67

i) her5 expression as a function of IWR-1 and SU5402 presence.

\[ y_{her5} = \beta_{\text{Intercept}} + \left\{ \begin{array}{ll} \beta_{[SU5402]10} & \text{if } [SU5402] = 10 \\ 0 & \text{otherwise} \end{array} \right\} + \left\{ \begin{array}{ll} \beta_{[IWR1]20} & \text{if } [IWR1] = 20 \\ 0 & \text{otherwise} \end{array} \right\} \]

ii) her5 expression as a function of IWR-1 and SU5402 presence.

\[ y_{her5} = \beta_{\text{Intercept}} + \left\{ \begin{array}{ll} \beta_{[SU5402]10} & \text{if } [SU5402] = 10 \\ 0 & \text{otherwise} \end{array} \right\} + \left\{ \begin{array}{ll} \beta_{[IWR1]} & \text{if } [IWR1] = 10 \\ 0 & \text{otherwise} \end{array} \right\} \]

Initially reduced most strongly when 20 μM IWR-1 was applied, compared to 30 or 40 μM (Fig. 7A and B). Continued exposure to IWR-1 revealed that 20 μM had the strongest effect on spry4. In contrast, higher doses led to an elevated spry4 expression 4 hours after application relative to DMSO treated control embryos. After 6 hours exposure, all doses of IWR-1 caused a reduced expression of spry4, with the lower dose showing the strongest effect. This difference in the response of spry4 to low or high doses of IWR-1 suggests that a compensatory feedback loop may operate to promote spry4 expression in response to reduced bcat activity. A good candidate for this is FGF signaling, as Wnt and FGF signaling interact to maintain the isthmus and promote each other's activity.10,31
Figure 6. Tankyrase inhibition does not lead to linear reductions of bcat activity over time. Lateral views of 16.5 (A–D), 18 (E–H), 20 hpf (I–L) embryos processed by in situ hybridization to reveal expression of *lef1* expression following treatment with IWR-1 at 0, 20, 30, 40 μM IWR-1 from 14 hpf. Lateral views of 24 hpf embryos processed by in situ hybridization to reveal expression of *wnt1* expression following treatment with IWR-1 at 0, 20, 30, 40 μM IWR-1 from 14 hpf. Isthmus (i). Scale bars: 100 μm.

Figure 5 (See page 9). Tankyrase activity does not affect positioning of MTN neurons or FGF directed *her5* expression in the dorsal midbrain. Box plot of the number of MTN neurons (A) or MTN-isthmus distance (scaled by midbrain size, B) in 2 separate clutches of embryos (red, blue) treated with 0, 20, 30, 40 μM IWR-1 from 14–24 hpf (n = 10 for each condition). Box plot of MTN-isthmus distance (scaled) in 24 hpf embryos treated with DMSO (red) or 10μM SU5402 (blue) in conjunction with IWR-1 (C, n = 10 for each condition). Dot plot of MTN neuron number relative to MTN-isthmus distance (scaled) for embryos treated with IWR-1 (0, 20, 30, 40μM) and SU5402 (0, 10μM) from 14 hpf (D). A correlation test reveals no correlation between neuron number and distance (R = 0.028, n = 10 for each condition). Dot plot of MTN-isthmus distance (scaled) relative to MTN neuron number (E) in 24 hpf control embryos (red) or Tg[hsp70:dlk1b-gfp] embryos expressing dkk1b (green) from 16.5 hpf. A correlation test reveals no correlation between MTN neuron number and distance (R = 0.48, n = 10 for each condition). Lateral views of 18 hpf embryos processed in situ hybridization to reveal expression of *her5* (blue, bracket indicates expression extent in dorsal midbrain) and *pax6* (red) following treatment with IWR-1 at 0, 20, 30, 40 μM IWR-1 from 14 hpf (F). A line plot of the *her5* expression domain in the dorsal midbrain (scaled to midbrain size) in embryos treated with IWR-1 at 0, 20, 30, 40 μM from 14 hpf at 16.5, 18, 20 hpf (J, n = 10 for each condition). Box plot of *her5* expression domain in the dorsal midbrain (scaled) in 24 hpf embryos treated with IWR-1 at 0, 20, 30 μM and SU5402 at 0 (red) and 10μM (blue) from 14 hpf (K, n = 10 for each condition). Isthmus (i). Scale bars: 100 μm.
We used the model of Lee et al.\(^4\) to examine how changing the rate at which Axin is ubiquinated by Tnk affects bcat activity. We modified the model such that the Axin degradation term was dependent on the concentration of Tnk:

\[
k_{15} [\text{Axin}] \rightarrow k_{15}' [\text{Tnk}][\text{Axin}]
\]

Therefore, adding IWR-1 will reduce the contribution of Tnk to the rate \((k_{15})\) at which Axin is degraded and so decrease this rate overall. A plot of Axin protein relative to different rates of Axin degradation reveals that at high IWR-1 doses (corresponding to low concentrations of Tnk), Axin protein accumulates (Fig. 8A). This corresponds with a decrease in free bcat. We wondered how Axin concentration (and thus Tnk activity) was related to bcat concentration in the model and observed a nonlinear response for the bcat, divided into 2 regions (Fig. 8B): a flat region corresponding to very low Axin concentrations and an inversely linear region corresponding to higher concentrations, described by the (fitted) power law equation:

\[
[bcat] = 0.078[\text{Axin}]^{-1.003}
\]

This linear region corresponds to Axin concentrations measured from Xenopus eggs and used for construction of the

Figure 7. spry4 shows a bivalent response to changes in Wnt and FGF signaling. Polynomials were fitted against the spatial expression of spry4 in the dorsal midbrain (\(\mu\text{m}\)) at 16.5, 18, 20 hpf following treatment with IWR-1 from 14 hpf (A) and showed a good fit \((R^2 = 0.7201, n = 10\) for each condition). A line plot of the spry4 expression domain (scaled to midbrain size) in the same embryos (B) reveals that treatment with 20\(\mu\)M IWR-1 had the strongest affect \((n = 10\) for each condition). Lateral views of 20 hpf embryos processed by in situ hybridization to reveal spry4 (blue) and pax6 (red) expression following treatment from 14 hpf with DMSO (C), 20\(\mu\)M IWR-1 (D), 30\(\mu\)M IWR-1 (E), 10\(\mu\)M SU5402 (F), 20\(\mu\)M IWR-1 with 10\(\mu\)M SU5402 (G), or 30\(\mu\)M IWR-1 with 10\(\mu\)M SU5402 (H). Isthmus (i). Scale bars: 100\(\mu\)m (C–H).
model, hence provides the region most likely occurring in a biological context. An analysis of how free bcat concentration changes relate to induction of a Wnt bcat induced phenotype or induction of siamois or Xnr3 in Xenopus embryos suggested it is the fold change of free bcat concentration that dictates the response to Wnt signaling.\textsuperscript{50,55} Using the same model as above, we investigated how the concentration of bcat changes relative to different rates of Axin degradation prior to and after Wnt stimulation (Fig. 8C). As before, high rates of Axin degradation lead to high levels of bcat. We then used this result to ask how the fold change of free bcat is affected by the Axin degradation rate (Fig. 8D). Intriguingly, we note that the fold change of bcat is predicted to be relatively high when Axin degradation is high or medium, but that it precipitously drops at low rates of Axin degradation. Our interpretation of this model is that IWR-1 will reduce the levels of free bcat, by promoting elevated levels of Axin, but also allow a greater fold change in bcat levels upon Wnt stimulation.

GSK-3 regulation of MTN positioning is independent of bcat activity

Our results reveal that BIO inhibits GSK-3 activity, leading to elevated bcat activity and an increase in the number of MTN neurons that show a more posterior location in the midbrain. In contrast, inhibition of bcat activity, through inhibition of Tankyrase enzyme or overexpression of dkk1, does not result in posteriorly located MTN neurons, but does lead to the formation of more neurons. As GSK-3 is important for regulating multiple intracellular signaling pathways, it may therefore have a bcat-independent role in controlling neurogenesis. To test if Wnt signaling can affect MTN positioning independently of GSK-3 function, we examined whether MTN development was altered in an axin1 mutant, masterblind (mbl). We observe elevated axin2 expression in mbl mutants indicative of increased bcat activity, similar to that observed after BIO treatment (Fig. 9A and B). We also note that mbl mutants have significantly more MTN neurons than in wildtype siblings, again similar to embryos treated with BIO (Fig. 9C). However, mbl mutants do not show posteriorly located neurons and there is no correlation between MTN number and positioning relative to the isthmus (Fig. 9D and E). This reveals that the increased number of MTN neurons caused by BIO treatment can be attributed to elevated bcat activity, but the posteriorly located MTN neurons observed in these embryos cannot be explained by increased bcat activity in the midbrain.

**Figure 8.** A model for bcat activity reveals differential responses to Tnk activity. The model of Lee et al.\textsuperscript{52} and Goentoro and Kirschner\textsuperscript{53} was modified such that Axin degradation (reaction 15) became linearly dependent on the concentration of Tankyrase (Tnk) with a new second-order kinetic constant \(k_{15}'\). The value of \(k_{15}'\) was assumed to be equal to the value of \(k_{15}(0.167)\), and the basal concentration of Tankyrase was assumed to be 1 (in arbitrary units). Steady-state values of Axin and b-catenin concentration (brackets) were obtained from the simulation of the model under varying concentrations of Tankyrase (both above and below the basal concentration indicated by a dashed vertical line) and plotted as functions of the total rate of degradation of Axin (A) and as a parametric plot (B). Next, the model was run under different rates of Axin degradation (\(k_{15}[\text{Tnk}]\)) until it reached a steady state (s1), then stimulated with addition of Wnt protein at \(t=20000\) and run until a steady-state was again reached (s2). These time courses were plotted to confirm a steady state was reached (C). For each value of \(k_{15}[\text{Tnk}]\) the fold change in the steady-state of [\(\beta\)-catenin] was calculated (s1/s2) and plotted (D).
Discussion

We have addressed how the interplay between Wnt and FGF activity controls the spatiotemporal specification of neurons in the developing midbrain. Our findings reveal that a variety of feedback and feed-forward regulatory loops operate to control both the level and site of activity of each pathway. This has implications for where neurons form in the brain during development, but also how many neurons will form and thus affect progenitor cell populations important for later-forming neurons. We find that FGF activity controls the number and positioning of MTN neurons, whereas Wnt signaling is primarily important for controlling the number of neurons that form. Furthermore, we identify a putative role for GSK-3 in modulating FGF-target gene activity and hence neuronal positioning, independent of bcat function.

Previously we could show that FGF activity regulates the number and positioning of MTN neurons in the midbrain and that this is mediated by FGF control of her5 expression. From these findings we predicted that alterations to FGF at early stages would affect subsequent development of later neuronal populations in the midbrain. We now present evidence that this occurs, as expansion of the MTN, due to reductions to FGF activity over a defined window of time, results in a smaller optic tectum. This reveals that a disruption to FGF activity across the midbrain upsets the controlled temporal onset of differentiation, needed for the appropriate spatial formation of discrete neuronal populations. Sustaining an appropriate level of FGF activity at the isthmus is therefore crucial for controlling where and when neurons are specified in the forming midbrain. There is a large body of evidence for an auto-regulatory interaction between Wnt and FGF signaling at the isthmus during midbrain development. Perturbations to this interaction are expected to affect midbrain patterning and development. In this study we have asked whether the interaction between Wnt and FGF occurs by control of bcat activity or of GSK-3. Inhibition of axin1 function, over-expression of dkk1 or over-activation of Axin function using IWR-1 all fail to alter MTN positioning, although they do increase the number of neurons that form. In contrast, GSK-3 inhibition promotes both the formation of extra neurons and the presence of posteriorly located neurons in the midbrain (Fig. 10A). We interpret these results to suggest that GSK-3 regulates FGF signaling across the midbrain independently of bcat. It further reveals that bcat activity controls the number of MTN neurons that form, independently of FGF signaling, but dependent on GSK-3 activity (Fig. 10B). Support for this interpretation comes from a screen to identify Wnt and FGF responsive genes in the developing tail bud of zebrafish. Similar to our approach, LiCl

Figure 9. Masterblind mutants possess more MTN neurons, but do not show a posterior displacement of MTN neurons. Lateral views of 24 hpf embryos processed by in situ hybridization to reveal elevated axin2 expression in midbrain (bracket) of masterblind mutants (mbl, B), relative to wildtype siblings (sibs, A). Box plot of the number of MTN neurons (C) or MTN-isthmus distance (scaled by midbrain size, D) in 24 hpf mbl mutants and sibs (n = 10 for each condition). There is a strong effect by mbl on MTN number (p = 2.8 x 10^-4) but not on MTN-isthmus distance (p = 0.064). Dot plot of MTN number against MTN-isthmus distance (scaled) for mbl mutants and sibs (E). A line of best fit reveals no correlation between MTN neuron number and distance (R = 0.19, n = 10 for each condition). Isthmus (i). Scale bars: 100μM (A,B).
and SU5402 were used as tools to manipulate each pathway. Many genes examined showed similar responses to both GSK-3 inhibition and inhibition of FGF receptor function. Furthermore, it was shown that inhibition of GSK-3 by LiCl led to phosphorylation of ERK and therefore activation of ERK signaling. This was interpreted to suggest that Wnt/ bcat signaling was controlling FGF signaling through MAPK/ERK activity. Based on our comparisons between BIO treatment relative to bcat overexpression, we would argue that GSK-3 has a bcat independent function in controlling MAPK/ERK activity.

We found that manipulations of bcat activity altered the number of MTN neurons that formed in the midbrain. This could be due to a role of Wnt signaling in controlling cell proliferation. Alternatively, it may reflect a role of Wnts in controlling neurogenesis. Recent findings have shown that Wnt/ bcat signaling can regulate neurogenesis in the flatworm Platynereis and regulates expression of neurogenic genes Neurogenin1, Neurogenin2 and NeuroD in mouse.24,25,57 We have previously shown that MTN development in the midbrain is not regulated by neurogenin function in zebrafish suggesting that Wnt/ bcat are not directing neuronal differentiation through regulation of neurogenin genes.58 Intriguingly, the action of Wnt on neurogenesis in neural stem cells is influenced by the level of FGF activity.33 We note that in zebrafish, increasing bcat activity promotes the formation of more MTN neurons. When this is performed in the context of reduced FGF activity (by varying doses of SU5402) this effect is enhanced. This implies that in the midbrain neuronal differentiation is controlled by the action of both FGF and Wnt/ bcat signaling. When this is perturbed by enhancing or reducing bcat activity (by expressing dkk1), we observe commensurate changes to the number of neurons that form in the midbrain. We have previously shown that temporal application of BIO at stages when MTN neurons start to differentiate does not alter proliferation, but does cause an increase in MTN number.34 We suggest that this reveals a role of Wnt/ bcat signaling in controlling the process of neuronal differentiation in the midbrain.

The targeted inhibition of Wnt/ bcat activity is important for treatment of many diseases and syndromes that involve aberrant Wnt signaling.59 Tankyrase enzymes have been the focus for many such efforts, due to their important functions in degrading and so limiting Axin protein availability. The IWR and XAV939 compounds selectively inhibit Tnk, resulting in an increase in Axin protein and hence increased bcat degradation by the bcatDC.11,53 Initial reports describing the effect of IWR-1 dose on bcat activity using the SuperTopFlash assay showed that an approximate linear response occurs relative to dose. We find that in vivo, IWR-1 does not affect bcat activity in a linear manner. We note that Wnt/ bcat responsive genes lef1 and spry4 show a
non-linear response to IWR-1 that changes relative to the duration of exposure. We also find that the concentration of IWR-1 alters the response over time. One intriguing observation we make is that low doses of IWR-1 initially cause a more severe inhibition of bcat responsive genes than a higher dose. Over time, higher concentrations of IWR-1 result in greater inhibition of bcat-dependent responses than lower concentrations. This change in response of bcat-responsive genes to different doses of IWR-1 suggests compensatory feedback loops modulate their response.

We have found that in the midbrain, FGF activity is required for expression of wnt1 and controls bcat activity. Likewise, bcat is able to upregulate expression of fgf8 and FGF target gene expression in the presence of SU5402. The interaction between Wnt and FGF signaling to maintain expression of their respective ligands in the isthmus is well established and occurs by a positive feedback loop.5–4 One putative explanation for the differential effects of IWR-1 dosage on Wnt-target genes may therefore be due to feedback from FGF signaling to promote elevated bcat signaling. In support of this, we note that higher doses of IWR-1 cause a rapid decrease in bcat activity and leads to increased unt1 expression, similar to that seen by over-activation of FGF signaling. The varying response of bcat-dependent gene expression in relation to IWR-1 dose, suggests that FGF-dependent feedback loop induce an oscillatory response. Such oscillatory behavior is a prediction of models generated to explain robustness during Wnt/ bcat signaling.3–4 Our interpretation of the results we observe in vivo, is that high doses of IWR-1 promote an FGF-mediated feedback mechanism leading to an upregulation of unt1 expression. Elevated levels of Wnt protein will promote bcatDC disassociation, until bcat-induced Axin2 levels rise sufficiently to overcome Wnt action on the bcatDC and bcat activity is then repressed. Our modification of a model for bcat activity indicates that when Axin degradation is low, the fold change is relatively insensitive to small changes in the degradation rate, but that it is far more sensitive to small changes at higher rates of degradation. This is result is analogous to previous analyses of bcat fold changes, which predicted sensitive and insensitive regions as a consequence of modifying the bcat degradation rate.5–9 It would thus be valuable to further determine how the concentration of free bcat respond to differing concentrations of IWR-1 concentration over time and how this corresponds to the relative concentrations of Axin1 and Axin2. Even more importantly, it will be necessary to show how bcat-activated genes respond to Tnk inhibitors in vivo, to understand how robustness in signaling pathway activity impacts on the biological outputs of drugs that aim to modulate Wnt/ bcat.

In summary, we show that components of the Wnt/ bcat pathway controls 2 aspects of midbrain development. GSK-3 acts to modulate FGF activity at the isthmus and thus controls the spatiotemporal differentiation of early neuronal populations, such as the MTN, across the midbrain. This function of GSK-3 appears to be independent to its role in regulating bcat, which acts to control the number of neurons that form. How these 2 functions of Wnt signaling are integrated is unclear. One hypothesis is that GSK-3 is required for normal activation of intracellular FGF targets, such as ERK. Thus, the interplay between Wnt/ bcat and FGF signaling occurs at a number of levels and involves a complex set of feedback loops to control their relative activity. Perturbations to any one component will lead to compensatory activity, inducing some degree of oscillatory response. In the presence of small molecular inhibitors, which do not respond dynamically to such feedback loops, oscillations will be more pronounced until they eventually reach a new equilibrium. As recently highlighted, this is relevant for understanding how cells in vivo may respond to drugs that target Wnt/ bcat activity.5–9 It is therefore crucial to target the most appropriate component of this pathway for effective inhibition of bcat activity with minimal interference to other important signalling pathways.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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