

This copy is for your personal, non-commercial use only.

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by [clicking here](#).

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines [here](#).

The following resources related to this article are available online at www.sciencemag.org (this information is current as of February 7, 2010):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:

<http://www.sciencemag.org/cgi/content/full/326/5958/1406>

Supporting Online Material can be found at:

<http://www.sciencemag.org/cgi/content/full/1178712/DC1>

A list of selected additional articles on the Science Web sites **related to this article** can be found at:

<http://www.sciencemag.org/cgi/content/full/326/5958/1406#related-content>

This article **cites 38 articles**, 22 of which can be accessed for free:

<http://www.sciencemag.org/cgi/content/full/326/5958/1406#otherarticles>

This article appears in the following **subject collections**:

Development

<http://www.sciencemag.org/cgi/collection/development>

Planarian Hh Signaling Regulates Regeneration Polarity and Links Hh Pathway Evolution to Cilia

Jochen C. Rink,* Kyle A. Gurley,* Sarah A. Elliott, Alejandro Sánchez Alvarado†

The Hedgehog (Hh) signaling pathway plays multiple essential roles during metazoan development, homeostasis, and disease. Although core protein components are highly conserved, the variations in Hh signal transduction mechanisms exhibited by existing model systems (*Drosophila*, fish, and mammals) are difficult to understand. We characterized the Hh pathway in planarians. Hh signaling is essential for establishing the anterior/posterior axis during regeneration by modulating *wnt* expression. Moreover, RNA interference methods to reduce signal transduction proteins *Cos2/Kif27/Kif7*, *Fused*, or *Iguana* do not result in detectable Hh signaling defects; however, these proteins are essential for planarian ciliogenesis. Our study expands the understanding of Hh signaling in the animal kingdom and suggests an ancestral mechanistic link between Hh signaling and the function of cilia.

The Hh signaling pathway plays numerous evolutionarily conserved roles in the regulation of cell growth and patterning during the embryonic and postembryonic development of animals as diverse as fruit flies and humans.

Department of Neurobiology and Anatomy, Howard Hughes Medical Institute, University of Utah School of Medicine, 401 MREB, 20 North 1900 East, Salt Lake City, UT 84103, USA.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: sanchez@neuro.utah.edu

The misregulation of this pathway has equally profound consequences, resulting in defects such as cyclopia and tumorigenesis in mammals. Secreted Hh protein alters gene transcription by binding the cell-surface receptor Patched (Ptc), preventing repression of the seven-membrane-spanning receptor Smoothened (Smo) by Ptc. This activates Gli transcription factors and inactivates their inhibitor Suppressor of Fused (SuFu). Despite conservation of these core components and their mode of function (1, 2), Hh signal trans-

duction mechanisms appear to have diversified throughout evolution (3). *Drosophila* Hh signaling is cilia-independent and requires the kinesin Costal2 (4) (*Kif7/27* in vertebrates) and the kinase *Fused* (5). The mouse Hh pathway requires primary cilia (6, 7) and *Kif7* (8–10), but not *Fused* (11, 12). Zebrafish use cilia, *Kif7*, *Fused*, and *Iguana/Dzip1* (*Igu*) (13–19). *Caenorhabditis elegans* has lost a functional Hh pathway altogether (20). Because planarians belong to a group of animals that evolved independently from flies, fish, and mammals (fig. S1), an analysis of planarian Hh signaling could reveal how the mechanistic differences in a highly conserved signaling pathway arose.

Systematic sequence homology searching of the *Schmidtea mediterranea* genome identified single homologs for planarian Hh (*Smed-hh*), Patched (*Smed-ptc*), Smoothened (*Smed-smo*), and Suppressor of Fused (*Smed-sufu*), but three Gli homologs (figs. S2 and S3). Of the Gli homologs, only *Smed-gli-1* exhibited an obvious role in Hh signaling. We cloned (see Supporting Online Material) and analyzed the expression of these planarian Hh components by in situ hybridization (Fig. 1, A to C, and fig. S4). *ptc* expression was reduced by RNA interference (RNAi) of pathway activators (*hh*, *smo*, and *gli-1*) and elevated by RNAi of pathway inhibitors (*ptc* and *sufu*) (Fig. 1B), which suggests that, as in other animals (21–23), *ptc* is a Hh target in planarians and its expression marks sites of Hh

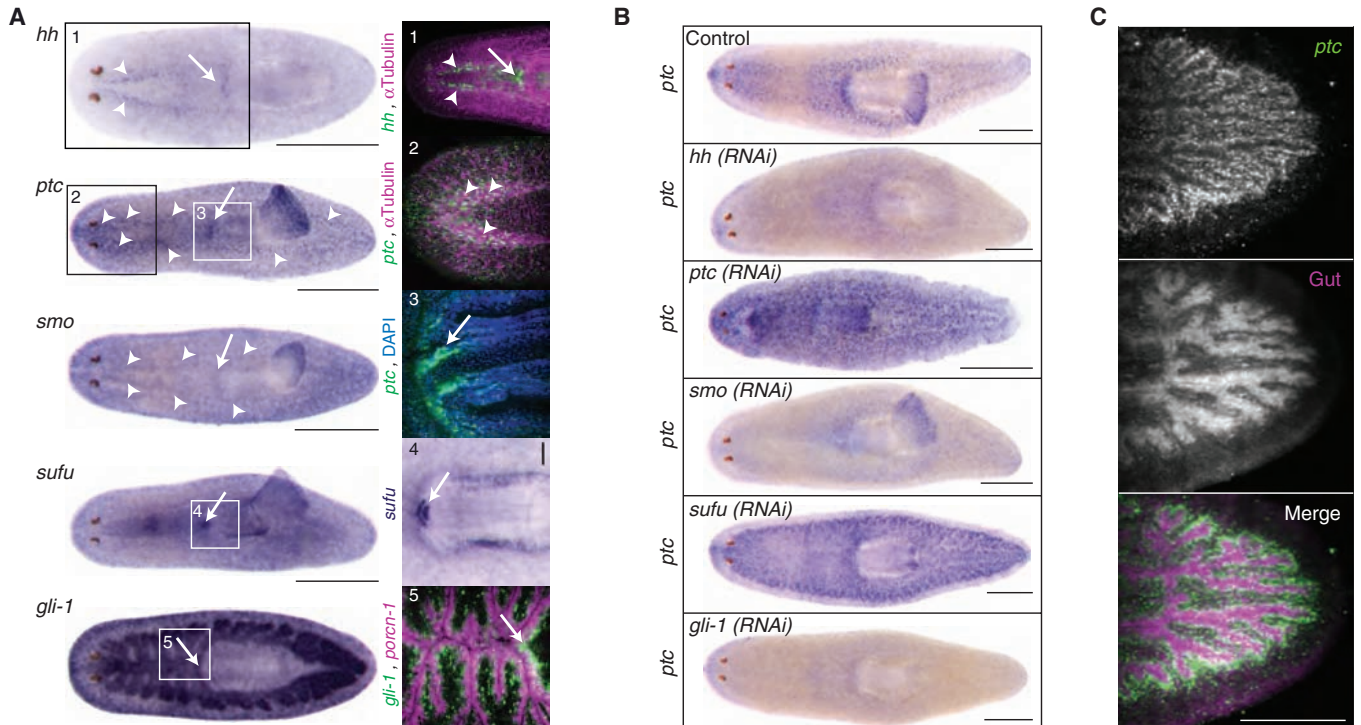


Fig. 1. Planarian Hedgehog signaling. (A) Gene expression in intact animals. Boxes magnified on right. 1, Epifluorescence image, *hh* (green), CNS (magenta, α -tubulin antibody). 2, Confocal image, ventral head, *ptc* (green), CNS (magenta, α -tubulin antibody). 3, Root of pharynx, *ptc* (green). Nuclei [blue, 4',6'-diamidino-2-phenylindole (DAPI)]. 4, *sufu* expression near root of pharynx. 5, *gli-1* (green), gut epithelium (magenta, *Smed-porc1* and

Smed-sialin). Scale bar, 0.5 mm. Arrowheads, ventral nerve cord. Arrow, root of pharynx. (B) *ptc* expression in RNAi-treated intact animals. The seemingly paradoxical up-regulation of *ptc* upon *ptc*(RNAi) results from the massive promotion of Hh signaling by *ptc*(RNAi). Scale bar, 0.5 mm. (C) *ptc* expression confocal images in *sufu*(RNAi) intact animals. Scale bar, 0.2 mm.

signaling. Complementary expression of *ptc*, *hh*, and *smo* throughout the central nervous system (CNS), and *hh*, *ptc*, *smo*, *sufu*, and *gli-1* near the root of the pharynx implicates these locations as possible sites of Hh activity (Fig. 1A and fig. S4). *gli-1* expression in cells surrounding the gut enterocytes (Fig. 1A) and particularly strong *ptc* up-regulation upon *sufu(RNAi)* in the same region (Fig. 1C) may indicate a conserved function of Hh in the gastrovascular system (24, 25). Additionally, mitotic activity was increased by *ptc(RNAi)* and *sufu(RNAi)* but decreased by *hh(RNAi)* (figs. S5 and S6), mirroring the mitotic effects of Hh in other organisms (26, 27). Altogether, these initial studies suggest that planarian Hh signaling likely has diverse functions in various adult tissues.

To investigate whether the Hh pathway contributes to the signaling network orchestrating planarian regeneration, we amputated the heads and tails of double-stranded RNA (dsRNA)-fed animals. Targeting the pathway activator *hh* left anterior regeneration unaffected but caused a range of posterior regeneration defects, including

reduced or absent tail tissue and concomitant changes in posterior marker expression (Fig. 2, A to B', and fig. S7). Conversely, RNAi against the pathway inhibitor *ptc* left posterior regeneration unaffected but caused anterior-specific defects, including tail instead of head formation and striking changes in marker expression (Fig. 2, D to F', fig. S7, and movies S1 and S2). Targeting *gli-1* and *smo* produced identical regeneration phenotypes to *hh(RNAi)*, and *sufu(RNAi)* resembled *ptc(RNAi)* (fig. S8), establishing tail or head regeneration defects as a general consequence of decreased or increased Hh signaling, respectively. Systematic RNAi dosage experiments ranked the range of phenotypes according to severity. Three observations are particularly noteworthy. First, "headless" animals expressed neither head nor tail markers anteriorly (Fig. 2, E' and E'') but expressed a marker for intermediate anterior cell fate (fig. S9), reminiscent of dose-dependent roles for Hh in other contexts (28). Second, "cyclopic" animals resulted from increased Hh signaling. The same phenotype occurs in vertebrates (29) but is caused by decreased Hh signaling. This

difference, along with lack of expression of *Smed-hh* along the planarian midline, suggests that the midline function of Hh in vertebrates is not conserved in planarians. Third, SuFu has a prominent role in planarians, which is similar to vertebrates but different from *Drosophila* (30). RNAi combination of two pathway activators or inhibitors enhanced the respective phenotypes, whereas activator-inhibitor combinations suppressed each other (fig. S10). However, besides the expected and predominant function of Smo as a pathway activator, these experiments also indicated a cryptic inhibitory activity, but the mechanistic basis of this effect is currently unclear. Combined with regeneration time course experiments showing that Hh-related phenotypes originate during early phases of regeneration (fig. S11), our data demonstrate that the different phenotypic classes resulting from altered Hh signaling constitute a series of anterior/posterior (A/P) patterning defects and that early Hh signaling is necessary and sufficient for tail regeneration.

The early requirements for elevated Hh signaling in tails and reduced Hh signaling in heads mirrors those for β -catenin signaling (31–33). In addition, diluted dosages of *APC-1(RNAi)*, which elevate β -catenin activity (31), produced a range of phenotypes quite similar to *ptc(RNAi)* (fig. S12). Combining doses of *ptc(RNAi)* and *APC-1(RNAi)* that by themselves elicited only weak defects led to a striking increase in phenotype severity (Fig. 3A). Moreover, a single feeding of *β catenin-1(RNAi)* in *ptc(RNAi)*-fed animals completely suppressed the *ptc(RNAi)* "two-tail" phenotype, causing head formation at both anterior and posterior wounds (Fig. 3B). Thus, the Hh and β -catenin pathways synergize functionally to specify tails, and tail induction by elevated Hh signaling likely depends on β -catenin activity.

Because a Wnt ligand (*Smed-wntP-1*) was recently implicated in activating β -catenin during tail regeneration (34, 35), we examined whether *wnt* expression was regulated by Hh signaling. One day after amputation, *wntP-1* expression was reduced in *hh(RNAi)* animals and strongly increased in *ptc(RNAi)* animals (Fig. 3C, top). In contrast, *wntP-1* expression was not altered in *β catenin-1(RNAi)* or *APC-1(RNAi)* animals (Fig. 3C, bottom), ruling out indirect polarity-associated effects. Expression of an additional *wnt* gene functioning in tail regeneration (*Smed-wnt11-2*) (34) showed a dependence on both Hh and β -catenin pathway activity (fig. S13). Unchanged *ptc* expression in *β catenin-1(RNAi)* or *APC-1(RNAi)* animals suggested that β -catenin may not reciprocally control Hh signaling (fig. S14). *wntP-1(RNAi)* suppressed the *ptc(RNAi)* phenotypes at anterior wounds (Fig. 3D) and strongly enhanced the *hh(RNAi)* phenotypes at posterior wounds, synergistically leading to the appearance of a posterior head in 20% of *wntP-1(RNAi);hh(RNAi)* animals (Fig. 3E). These data indicate that Hh-mediated *wntP-1* expression is likely responsible for the posteriorizing effect of *ptc(RNAi)* and that improved *hh(RNAi)* efficiency might be suffi-

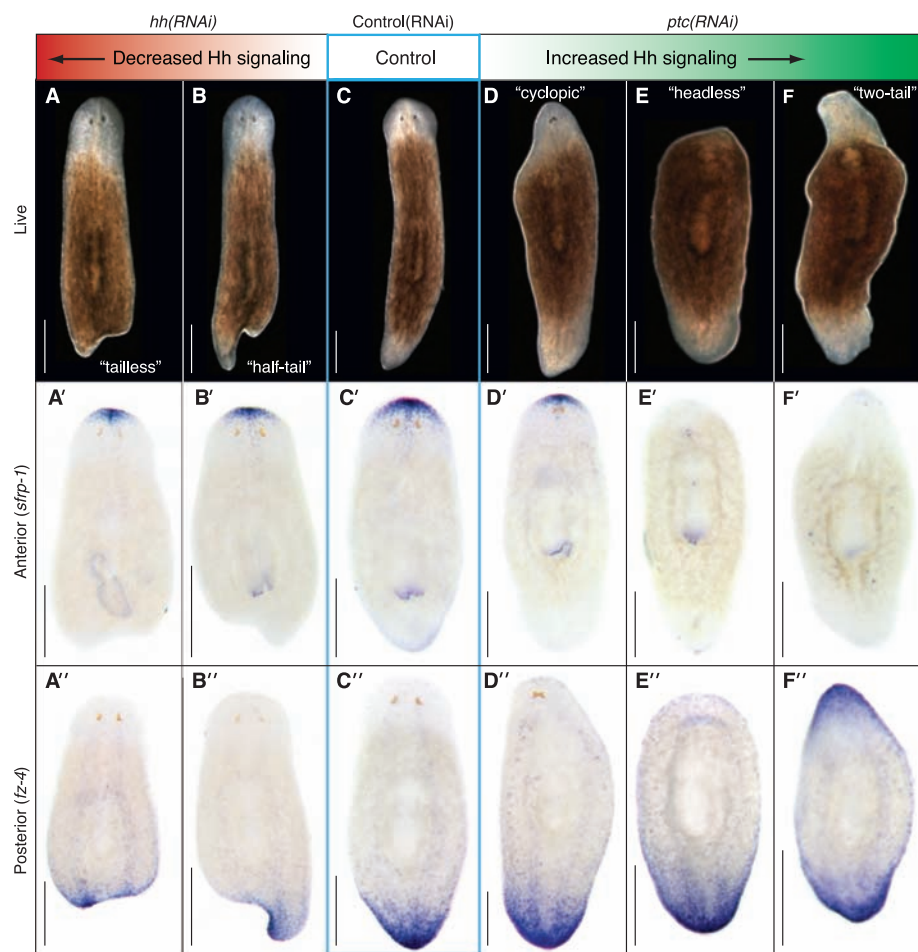
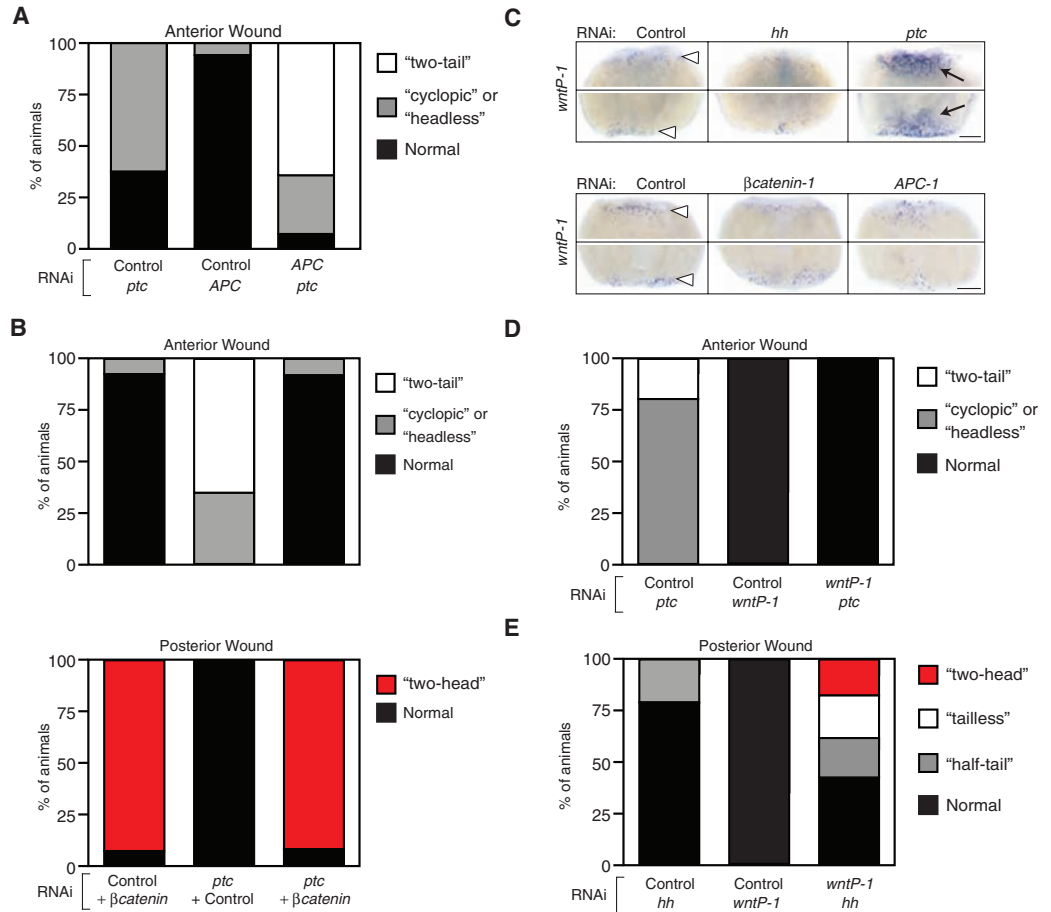


Fig. 2. Misregulated Hh signaling results in A/P patterning defects. (A to F) Live images of regenerating trunk fragments 14 days after amputation. Decreased Hh signaling achieved by *hh(RNAi)* (A to B'), and increased signaling by *ptc(RNAi)* (D to F'). Phenotypes are arranged according to severity. (A' to F') Expression of anterior marker [*Smed-sFRP-1* (31, 33)]. (A'' to F'') Expression of posterior marker [*Smed-zf-4* (31)].

Fig. 3. Hh specifies A/P fate through interaction with Wnt/ β -catenin signaling. **(A and B)** Quantification of double-RNAi experiments scored for anterior or posterior regeneration defects. Relative frequency of indicated phenotypes in a cohort of trunk fragments scored 14 days after amputation. **(A)** $N > 15$ animals per condition. **(B)** $N > 20$ animals per condition. **(C)** *wntP-1* expression at 1 day after amputation. White arrowheads, expression at both anterior (upper panels of each set) and posterior (lower panels of each set) wounds in control animals. Black arrows, up-regulated expression in *ptc(RNAi)*. Scale bars, 0.2 mm. **(D and E)** Quantification of double-RNAi experiments scored for **(D)** anterior and **(E)** posterior regeneration defects. Relative frequency of indicated phenotypes in trunk fragment cohort scored 14 days after amputation. $N > 21$ animals per condition.



cient for head formation from posterior wounds. In intact animals, *wnt* expression did not respond to alterations of Hh pathway activity (fig. S15), which suggests that Hh control of *wnt* expression is specific to the establishment of A/P polarity during regeneration.

The expression patterns of *hh*, *ptc*, and *wntP-1* did not show a posterior bias, as might be expected from their requirement for tail formation (Fig. 3C and fig. S16). Whereas such bias could be short-lived or difficult to detect, symmetric Hh activity and *wnt* expression would require additional components to specifically inhibit β -catenin activity anteriorly. Nonetheless, our data clearly demonstrate synergies between the Hh and Wnt signaling pathways during regeneration. We conclude that Hh influences A/P fate by controlling *wnt* expression.

The range of Hh-related regeneration defects from subtle to severe (Fig. 2) provided a sensitive readout to assess whether cilia or other signal transduction components play a role in the planarian Hh pathway. We cloned planarian homologs of intraflagellar transport (IFT) proteins (*Smed-IFT52*, *Smed-IFT88*, *Smed-IFT172*, and *Smed-kif3b*) (fig. S17), which are universally required for the assembly of cilia (36). Animals fed dsRNA targeting any of the IFT components lost their cilia-dependent gliding ability, advancing more slowly by waves of whole-body contraction and extension (inchworming) instead (Fig. 4A, fig. S18, and

movie S3). Consistently, their cilia were severely shortened (Fig. 4B). Additionally, *IFT(RNAi)* animals developed edema (Fig. 4A, inset), likely due to impaired osmoregulation by their heavily ciliated protonephridia. Targeting Hh pathway components did not affect cilia (Fig. 4, A and B). Despite the prominent cilia defects, *IFT(RNAi)*-treated animals showed no evidence of altered Hh signaling during regeneration by morphology and early marker expression (fig. S19), and *ptc* expression was unaffected in the CNS, pharynx, and gut (fig. S20A). Although we cannot entirely exclude subtle, nonregeneration-related, or residual cilia contributions (17), our data did not uncover a role for cilia in planarian Hh signaling.

We next cloned the single planarian homologs of *fused* (*Smed-fused*), *cos2/kif27/kif7* (*Smed-kif27*), and *iguana* (*Smed-iguana*) (fig. S17), which were all discovered because of mutations severely affecting Hh signaling in *Drosophila* (4, 5) or zebrafish (18, 19), respectively. Silencing *fused*, *kif27*, or *iguana* neither perturbed *ptc* expression (fig. S20B) nor elicited Hh-related regeneration defects (fig. S21). Hence, these components are unlikely to function in planarian Hh signaling, but the same caveat raised for the IFT genes applies. Intriguingly, as for *iguana(RNAi)* (37), *fused(RNAi)* or *kif27(RNAi)*-treated worms instead displayed compromised mobility (Fig. 4C), inchworming, tissue edema (Fig. 4D) and complete loss of cilia (Fig. 4E). Furthermore, the expression patterns of

iguana and *kif27* closely resembled those of cilia genes (fig. S22). These data demonstrate by multiple functional and morphological criteria that *fused*, *kif27*, and *iguana* are essential for planarian ciliogenesis.

This finding establishes that the ciliogenesis functions of Fused, Kif7, and Iguana are not vertebrate-specific (15, 17) but instead are ancestral. The use of cilia, Fused, Kif7, and Iguana in the zebrafish Hh pathway (13–15, 18, 19), cilia and Kif7 in the mouse Hh pathway (8–10), and Fused and Cos2 in the *Drosophila* Hh pathway (3) further implies that all three model organisms rely on cilia and/or ancient cilia components for Hh signaling. Thus, the association between Hh signaling and cilia is most likely also ancestral (fig. S23). This conclusion is based solely on the ciliogenesis functions of Fused and Cos2/Kif7/Kif7 and is unaffected by whether they also function in planarian Hh signaling. In fact, uncovering evidence to this effect would further strengthen the argument for an ancestral connection.

Our findings suggest that the perplexing diversity in Hh signal transduction mechanisms among flies, fish, and mammals arose from group-specific losses of the ancestral association between cilia and Hh signaling (fig. S23). This raises the question of why core components are highly conserved, yet the contribution of cilia-related proteins to Hh signaling is variable. The dynamic

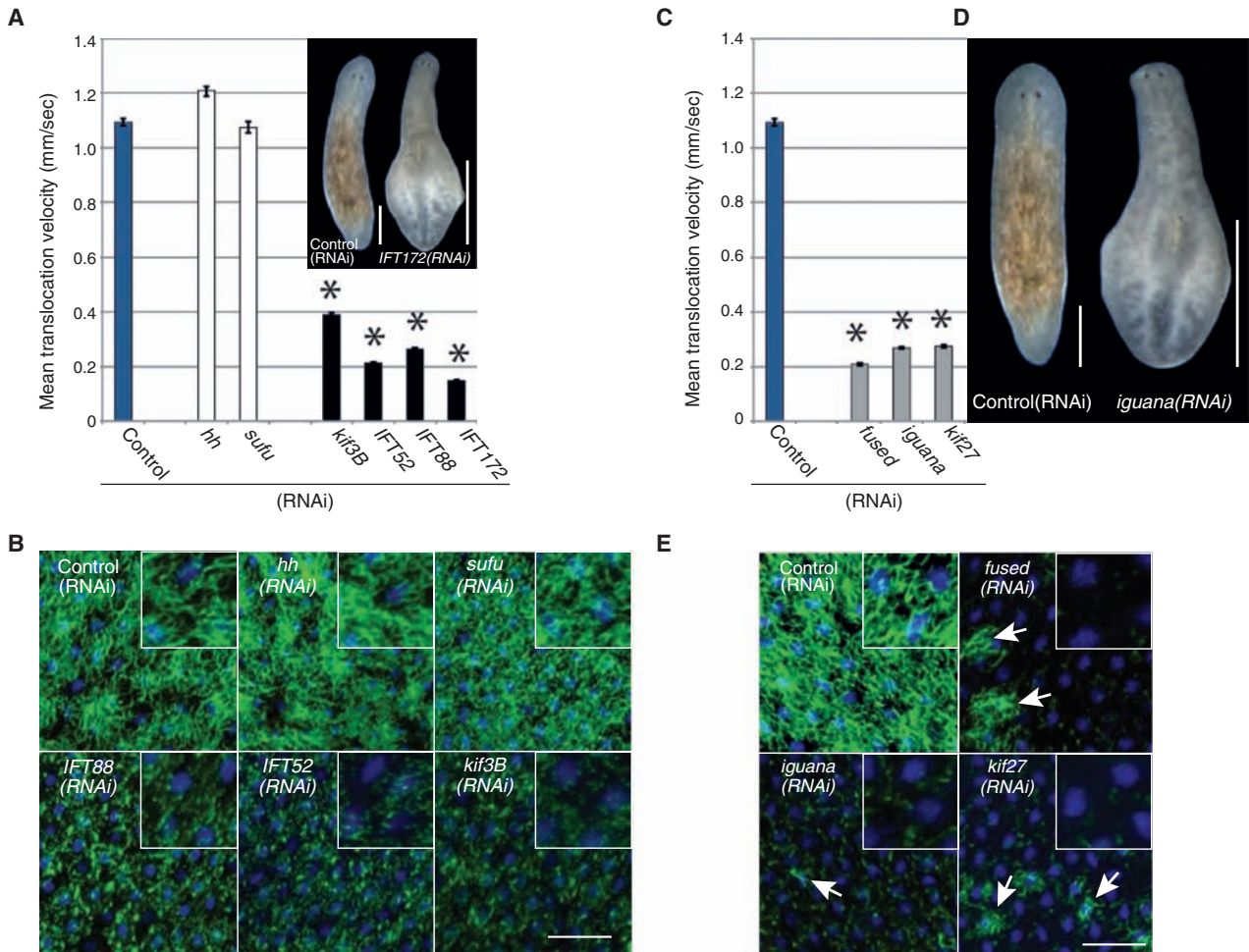


Fig. 4. Hh signaling is cilia-independent, and *kif27*, *fused*, and *iguana* are cilia genes in planarians. **(A)** Mean translocation speed quantified from movies of animals having received the indicated RNAi treatments. Error bars, SEM. *, $P < 0.01$ versus control (one-way analysis of variance). Data is from ≥ 4 movies with $N \geq 5$ animals per movie. (Inset) Example of tissue edema caused by *IFT172(RNAi)*. Scale bars, 0.5 mm. **(B)** Ventral cilia confocal projections (green, acetylated tubulin antibody), overlaid with nuclei (blue, DAPI) to demonstrate epithelial integrity. RNAi treatments as indicated. Insets,

zoom. Punctate pattern, remaining cilia stumps. Scale bars, 50 μ m. **(C)** Translocation speed calculated as in (A). **(D)** Tissue edema in *iguana(RNAi)* animal 14 days after amputation. Scale bar, 0.5 mm. **(E)** Ventral cilia confocal projections (green, acetylated tubulin antibody) overlaid with nuclei (blue, DAPI) as in (B). Arrows, remaining tufts of cilia on cells not yet affected by RNAi. Residual staining in *fused(RNAi)*, *iguana(RNAi)*, and *kif27(RNAi)* animals due to non-cilia-related staining of subepithelial structures. Scale bar, 50 μ m.

shuttling of core components between subcellular compartments in both flies and vertebrates (9, 10, 38) may have originally been organized by cilia (providing a location) and the associated IFT complexes (providing the motors). The divergence of Hh signaling mechanisms could thus reflect the choice of a new location or motor for organizing the interplay between core components.

References and Notes

1. P. W. Ingham, M. Placzek, *Natl. Rev.* **7**, 841 (2006).
2. L. Lum, P. A. Beachy, *Science* **304**, 1755 (2004).
3. D. Huangfu, K. V. Anderson, *Development* **133**, 3 (2006).
4. J. C. Sisson, K. S. Ho, K. Suyama, M. P. Scott, *Cell* **90**, 235 (1997).
5. T. Preat et al., *Nature* **347**, 87 (1990).
6. D. Huangfu, K. V. Anderson, *Proc. Natl. Acad. Sci. U.S.A.* **102**, 11325 (2005).
7. D. Huangfu et al., *Nature* **426**, 83 (2003).
8. H. O. Cheung et al., *Sci. Signal.* **2**, ra29 (2009).
9. S. Endoh-Yamagami et al., *Curr. Biol.* **19**, 1320 (2009).
10. K. Liem Jr., M. He, P. Ocbina, K. Anderson, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 13377 (2009).
11. M. H. Chen, N. Gao, T. Kawakami, P. T. Chuang, *Mol. Cell. Biol.* **25**, 7042 (2005).
12. M. Merchant et al., *Mol. Cell. Biol.* **25**, 7054 (2005).
13. S. Y. Tay, P. W. Ingham, S. Roy, *Development* **132**, 625 (2005).
14. C. Wolff, S. Roy, P. W. Ingham, *Curr. Biol.* **13**, 1169 (2003).
15. C. W. Wilson et al., *Nature* **459**, 98 (2009).
16. P. Aanstad et al., *Curr. Biol.* **19**, 1034 (2009).
17. P. Huang, A. F. Schier, *Development* **136**, 3089 (2009).
18. K. Sekimizu et al., *Development* **131**, 2521 (2004).
19. C. Wolff et al., *Genes Dev.* **18**, 1565 (2004).
20. T. R. Burglin, P. E. Kuwabara, *WormBook* **2006**, 1 (28 January, 2006); 10.1895/wormbook.1.76.1.
21. L. V. Goodrich, R. L. Johnson, L. Milenkovic, J. A. McMahon, M. P. Scott, *Genes Dev.* **10**, 301 (1996).
22. Y. Chen, G. Struhl, *Cell* **87**, 553 (1996).
23. V. Marigo, M. P. Scott, R. L. Johnson, L. V. Goodrich, C. J. Tabin, *Development* **122**, 1225 (1996).
24. D. Kang et al., *Development* **130**, 1645 (2003).
25. F. Simonnet, J. Deutsch, E. Queinnet, *Dev. Genes Evol.* **214**, 537 (2004).
26. S. Takashima, M. Mkrtychan, A. Younossi-Hartenstein, J. R. Merriam, V. Hartenstein, *Nature* **454**, 651 (2008).
27. J. J. Trowbridge, M. P. Scott, M. Bhatia, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 14134 (2006).
28. P. W. Ingham, A. P. McMahon, *Genes Dev.* **15**, 3059 (2001).
29. C. Chiang et al., *Nature* **383**, 407 (1996).
30. T. Preat, *Genetics* **132**, 725 (1992).
31. K. A. Gurley, J. C. Rink, A. Sánchez Alvarado, *Science* **319**, 323 (2008).
32. M. Iglesias, J. L. Gomez-Skarmeta, E. Salo, T. Adell, *Development* **135**, 1215 (2008).
33. C. P. Petersen, P. W. Reddien, *Science* **319**, 327 (2008).
34. T. Adell, E. Salo, M. Boutros, K. Bartscherer, *Development* **136**, 905 (2009).
35. C. P. Petersen, P. W. Reddien, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 17061 (2009).
36. L. Pedersen, J. Rosenbaum, *Curr. Top. Dev. Biol.* **85**, 23 (2008).
37. P. W. Reddien, A. L. Bermanage, K. J. Murfitt, J. R. Jennings, A. Sánchez Alvarado, *Dev. Cell* **8**, 635 (2005).
38. S. Y. Wong, J. F. Reiter, *Curr. Top. Dev. Biol.* **85**, 225 (2008).

39. We thank the Sánchez laboratory for helpful comments and C. Adler for sharing data on *iguana*. Work supported by NIH National Institute of General Medical Sciences grants RO-1 GM57260 to A.S.A. and F32GM082016 to K.A.G. J.C.R. was funded by the European Molecular Biology Association. A.S.A. is a Howard Hughes Medical Institute investigator. All sequences associated with this

study have been deposited in GenBank and have accession numbers GQ337474 to GQ337490.

Supporting Online Material

www.sciencemag.org/cgi/content/full/1178712/DC1
Materials and Methods
Figs. S1 to S23

Movies S1 to S3
References

6 July 2009; accepted 14 October 2009
Published online 22 October 2009;
10.1126/science.1178712
Include this information when citing this paper.

Promoting Interest and Performance in High School Science Classes

Chris S. Hulleman^{1*} and Judith M. Harackiewicz²

We tested whether classroom activities that encourage students to connect course materials to their lives will increase student motivation and learning. We hypothesized that this effect will be stronger for students who have low expectations of success. In a randomized field experiment with high school students, we found that a relevance intervention, which encouraged students to make connections between their lives and what they were learning in their science courses, increased interest in science and course grades for students with low success expectations. The results have implications for the development of science curricula and theories of motivation.

Many educators and funding agencies share the belief that making education relevant to students' lives will increase engagement and learning (1–6). However, little empirical evidence supports the specific role of relevance in promoting optimal educational outcomes, and most evidence that does exist is anecdotal or correlational (1–3, 5, 7, 8). The purpose of our research is to demonstrate how an intervention specifically designed to enhance the relevance of science to students' lives can enhance interest in science and classroom performance, particularly for students who are most at risk for being disengaged from school.

Numerous curricular reform efforts have emphasized applying science to students' lives, such as providing out-of-school research experiences (7, 9), creating learning modules for specific topics [e.g., “Acids, bases, and cocaine addicts” (10, 11)], developing an undergraduate course [e.g., “The biology and chemistry of everyday life” (12, 13)], and redesigning the academic structure of entire high schools (14). For example, the Metro Nashville Public School District redesigned several of its high schools into career academies within which students can choose from thematically focused learning communities (15). The intention of these career academies is to enable students to “connect what they learn in school with their career aspirations and goals” (14). Although many of these programs have produced positive outcomes, such as improvements in retention in academic programs (13) or performance on achievement tests (7, 10–12), it is not clear that these effects were due to personal

relevance. These educational reforms are multifaceted, and an emphasis on relevance is just one of several components that may have contributed to the programs' outcomes. For example, other potentially effective components are small group instruction (12, 16), repeated exposure to the material (10), individual mentoring and teaching (14), individualized and/or team-based projects (7, 13, 16), hands-on activities (9), visualization exercises (11), increased autonomy (6), and increased knowledge development (17, 18).

Programs that emphasize personal relevance may be particularly empowering for students who are disengaged from school because of a lack of confidence. Students can become energized if they believe they are competent in science and can successfully perform classroom

tasks. As described by expectancy-value models of motivation (19), both an individual's expectancy for success and his or her perception of value for the activity facilitate student motivation. Research on expectancies reveals that expecting to successfully perform a task leads to greater persistence, performance, and interest in academic activities (19, 20). Thus, students who do not believe that they can do well in the classroom are at risk for performing poorly and becoming less interested in academics.

In addition to lacking confidence, students with low success expectancies may not perceive, or may have a harder time perceiving, relevance and value in their schoolwork (21). These students may require external support, from teachers or classroom activities, to foster or maintain task engagement (22). Interventions that facilitate the perception of relevance in a topic might promote attention and learning for students with low success expectancies (23). Instead of withdrawing from the activity, these students may become energized as they discover reasons for exerting effort and becoming more involved in learning (24). In contrast, more-confident students may not need this type of motivational boost because their effort and involvement in school are already strong (22, 24).

Reduced interest in academics is particularly problematic for long-term outcomes such as educational and career choices. Research on the development of interest (i.e., experiencing positive affect, value, and knowledge with an activity)

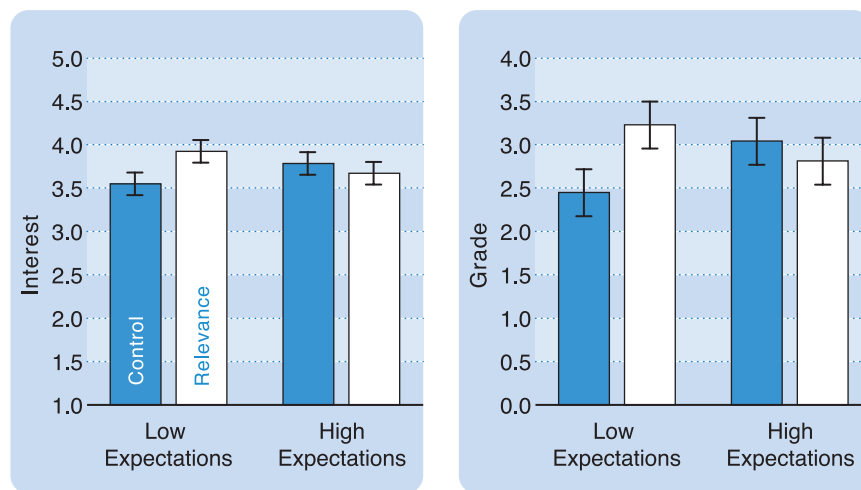


Fig. 1. Science interest (left) and course grades (right) as predicted by the relevance intervention and performance expectations. Predicted values are computed from the multiple regression equation for the interaction between the relevance intervention and performance expectations (low = -1 SD, high = $+1$ SD) on final course interest and second-quarter grades. Error bars represent ± 2 SEM (0.12 for interest and 0.28 for grades).

¹Department of Graduate Psychology, James Madison University, Harrisonburg, VA 22807, USA. ²Department of Psychology, University of Wisconsin–Madison, Madison, WI 53706, USA.

*To whom correspondence should be addressed. E-mail: hullemsc@jmu.edu