Improved tools for the Brainbow toolbox

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In the transgenic multicolor labeling strategy called ‘Brainbow’, Cre-loxP recombination is used to create a stochastic choice of expression among fluorescent proteins, resulting in the indelible marking of mouse neurons with multiple distinct colors. This method has been adapted to non-neuronal cells in mice and to neurons in fish and flies, but its full potential has yet to be realized in the mouse brain. Here we present several lines of mice that overcome limitations of the initial lines, and we report an adaptation of the method for use in adeno-associated viral vectors. We also provide technical advice about how best to image Brainbow-expressing tissue.

The discovery that recombinant jellyfish GFP fluoresces when expressed in heterologous cells1 has led to a vast array of powerful methods for marking and manipulating cells, subcellular compartments and molecules. The discovery or design of numerous spectral variants2–13 (fluorescent proteins collectively called XFPs; ref. 14) expanded the scope of the ‘GFP revolution’ by enabling discrimination of nearby cells or processes labeled with contrasting colors. At least for the nervous system, however, two or three colors are far too few because each axon or dendrite approaches hundreds or thousands of other processes in the crowded neuropil of the brain.

Several years ago, we developed a transgenic strategy called Brainbow15 that addresses this problem by marking neurons with many different colors. In this method, three or four XFPs are incorporated into a transgene, and the Cre-loxP recombination system16 is used to make a stochastic ‘choice’ of a single XFP to be expressed from the cassette. Because multiple cassettes are integrated at a single genomic site, and the choice within each cassette is made independently, combinatorial expression can endow individual neurons with 1 of ∼100 colors, providing nearby neurons with distinct spectral identities.

If Cre recombinase is expressed transiently, descendants of the initially marked cell inherit the color of their progenitor. Accordingly, the Brainbow method has been adapted for use in lineage analysis in non-neural tissues of mice17–21. In addition, it has been adapted for analyses of neuronal connectivity, cell migration and lineage in fish22,23 and flies24,25. In contrast, the method has been little used in the mouse nervous system26. We believe that the main reasons for this are limitations of the initial set of Brainbow transgenic mice. These include suboptimal fluorescence intensity, failure to fill all axonal and dendritic processes, and disproportionate expression of the ‘default’ (that is, nonrecombined) XFP in the transgene. We have now addressed several of these limitations, and we present here a new set of Brainbow reagents. In addition, we provide guidelines for imaging Brainbow-expressing tissue.

RESULTS Design of Brainbow 3.0 transgenes

As a first step in improving Brainbow methods, we sought XFPs with minimal tendency to aggregate in vivo, high photostability and maximal stability with respect to paraformaldehyde fixation. Because some XFPs that ranked highly in cultured cells performed poorly in vivo, we generated transgenic lines from 15 XFPs (Supplementary Table 1 and refs. 2–13). Of the XFPs tested in this way, seven were judged suitable: mTFP1, EGFP, EYFP, mOrange2, TagRFPt, tdTomato and mKate2.

From these XFPs, we chose three according to the criteria of minimal spectral overlap and minimal sequence homology. These XFPs were mOrange2 from a coral (excitation peak (Ex) = 549 nm, emission peak (Em) = 565 nm), EGFP from a jellyfish (Ex = 488 nm, Em = 507 nm) and mKate2 from a sea anemone (Ex = 588 nm, Em = 635 nm)2,9,11. Our reason for minimizing sequence homology was to ensure that the XFPs would be antigenically distinct, in contrast to spectrally distinct but antigenically indistinguishable jellyfish variants (EBFP, ECFP, EGFP and EYFP). Exploiting this property, we generated antibodies to the XFPs in different host species (rabbit anti-mCherry, anti-mOrange2 and anti-tdTomato; chicken anti-EGFP, anti-EYFP and anti-ECFP; and guinea pig anti-mKate2, anti-TagBFP and anti-TagRFP; Supplementary Table 1). Tests in transfected cultured cells confirmed a lack of cross-reactivity (data not shown).

Next we addressed the need to fill all parts of the cell evenly. Unmodified XFPs labeled somata so strongly that nearby processes were difficult to resolve, whereas palmitoylated derivatives, which targeted the XFPs to the plasma membrane, were selectively transported to axons and labeled dendrites poorly15. We therefore generated farnesylated derivatives27, which were trafficked to membranes of all neurites (see below).

On the basis of these results, we generated ‘Brainbow 3.0’ transgenic lines incorporating farnesylated derivatives of mOrange2, EGFP and mKate2. We retained the Brainbow 1 format15, in which

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incompatible wild-type and mutant loxP sites are concatenated so that Cre recombinase yields a stochastic choice among XFPs (Fig. 1a). We also retained two other features of the Brainbow 1 strategy. First, we used neuron-specific regulatory elements from the Thy1 gene because it promotes high levels of transgene expression in many, although not all, neuronal types; other promoter-enhancer sequences that we tested support considerably lower levels of expression. Second, we generated transgenic lines by injection into oocytes because this method leads to integration of multiple copies of the cassette and, thus, a broad spectrum of outcomes; by contrast, knock-in lines generated by homologous recombination contain one or two copies of the cassette (as heterozygotes or homozygotes, respectively) and, consequently, a smaller number of possible color combinations.

Design of Brainbow 3.1 and 3.2 transgenes
In Brainbow 1, 2 and 3.0 (Fig. 1a) and ref. 15, one XFP is expressed ‘by default’ in Cre-negative cells. The presence of a default XFP has both drawbacks and advantages. In cases of limited Cre expression, this XFP is expressed in a majority of cells, reducing spectral diversity among recombined neurons. On the other hand, incorporation of a default XFP allows one to screen numerous lines in the absence of a Cre reporter to assess the number and types of cells in which XFPs could be expressed following recombination.

To eliminate the default XFP while retaining the ability to assess expression in the absence of Cre, we adopted the following strategy. First, we incorporated three rather than two pairs of incompatible loxP sites, which allowed insertion of a ‘stop’ cassette (Fig. 1a). We also retained two other features of the Brainbow 1 strategy. First, we used neuron-specific regulatory elements from the Thy1 gene because it promotes high levels of transgene expression in many, although not all, neuronal types; other promoter-enhancer sequences that we tested support considerably lower levels of expression. Second, we inserted a fourth XFP, Phi-YFP (from the woodchuck hepatitis virus post-transcriptional regulatory element (WPRE), into the 3′ untranslated sequences of the cassette and, thus, a broad spectrum of outcomes; by contrast, knock-in lines generated by homologous recombination contain one or two copies of the cassette (as heterozygotes or homozygotes, respectively) and, consequently, a smaller number of possible color combinations.

Characterization of Brainbow 3 mice
We generated 31 lines of transgenic mice from the Brainbow 3.0, 3.1 and 3.2 cassettes. Offspring were crossed with several Cre transgenic lines, leading to multicolor spectral labeling of neuronal populations in numerous regions including cerebral cortex, brainstem, cerebellum, spinal cord and retina (Fig. 1b–f, Supplementary Table 2, Supplementary Fig. 2 and Supplementary Videos 1 and 2). The intensity of expression varied markedly among lines, making quantitative comparison of dubious value, but the most
Figure 2 | Improved visualization of neurons in Brainbow 3 mice. (a,b) Cerebellum from Brainbow 1.0 (a) and Brainbow 3.1 (line 3) L7-Cre (b) mice. Insets show high-magnification views of boxed regions. The farnesylated XFPs clearly label the fine processes and dendritic spines (b, inset arrows), which are missing in the cytoplasmic labeling (a, inset). (c,d) Retina from a Brainbow 3.0 (line D) Islet-Cre mouse expressing EGFP (blue), mOrange2 (green) and guinea pig anti-mKate2 (d) are shown. (e–h) Immunostained cerebellum section from Brainbow 3.2 (line 7) parvalbumin-Cre mouse. Separate channels of region boxed in e are shown in f–h. (i) Fraction of all labeled neurons that express EGFP, mOrange2 (mO2) or mKate2 (mK2) (n = 2,037 neurons from 15 regions of two brains). Scale bars: 40 µm (a,b), 20 µm (c,d), 25 µm (e–g), 10 µm (insets).

strongly expressing lines were those that incorporated the WPRE (Brainbow 3.2).

Analysis of these lines confirmed their advantages over Brainbow 1 and 2 lines. First, the use of farnesylated XFPs led the XFPs to concentrate at the plasma membrane (Fig. 1d). As a consequence, somata were less intensely labeled in Brainbow 3 than in Brainbow 1 mice, so processes could be visualized without saturation of the somata (Fig. 2a,b and Supplementary Fig. 3). Use of farnesylated XFPs also improved labeling of fine processes and dendritic spines (Fig. 2a,b). Second, the ability to immunostain all three XFPs led to enhancement of the intrinsic fluorescence without loss of color diversity (Fig. 2c,d and Supplementary Fig. 4). Third, XFP fluorescence was visible only in Cre-positive cells, thereby correcting the color imbalance caused by default XFP expression in cells that were Cre negative or cells that expressed Cre at low levels in Brainbow 1 and 2 lines (Fig. 2e–i and Supplementary Fig. 5). Thus, Brainbow 3 lines are likely to be more useful than Brainbow 1 and 2 lines for multicolor labeling.

Brainbow with self-excising Cre recombinase

In Brainbow 1–3 lines, the cassette encodes XFPs separated by loxP sites; Cre recombinase is supplied from a separate transgene. For analysis of connectivity in mouse mutants, breeding mice with two transgenes (Brainbow and Cre) into an already complex background is cumbersome. We therefore attempted to combine constructs encoding XFPs and Cre in a single cassette. In this transgene, called ‘Autobow’, we substituted a self-excising Cre recombinase38 for the stop sequences in Brainbow 3.1 (Fig. 3a). The Thy1 regulatory elements lead to expression of Cre in differentiated neurons; Cre then simultaneously activates an XFP and excises itself.

We generated three founder mice using this construct. Two were analyzed as adults, and both of these exhibited combinatorial expression of XFPs in multiple neurons (Fig. 3b and Supplementary Fig. 2e). We were concerned that precocious Cre activation in the germ line might lead to loss of the cassette. We therefore established a line from the third founder and examined mice in the second and sixth generations. Color range was limited in this line, perhaps because only a few copies had been integrated into the genome, but the variety of colors and level of expression were similar in both generations (Fig. 3c,d). Thus, Autobow transgenes can be stably maintained.

Brainbow using Flp recombinase and FRT sites

A second recombination system, orthogonal to Cre-loxP, could be used to independently control expression of distinct XFPs in, for example, excitatory and inhibitory neurons. In this way, the color of a neuron could denote cell identity, a feature lacking in currently available Brainbow lines15,17–20. We therefore tested a second recombination system, in which Flp recombinase acts on Flp recombinase target (FRT) sites. The Flp–FRT system has been used in conjunction with Cre-loxP in mice18 and in Brainbow-like transgenes in Drosophila24,25.

We tested previously described mutant FRT sites39,40 to find incompatible sets (Supplementary Fig. 6) and used these sets to construct ‘Flpbow’ lines (Fig. 4a). In one cassette, we fused the XFPs to an epitope tag41, which allowed for discrimination of cells labeled by Cre- and Flp-driven cassettes (Supplementary Fig. 7).
When Flpbow mice were mated to Flp-expressing mice\textsuperscript{42,43}, we observed multicolor labeling (Fig. 4b,c). Although the few lines tested to date exhibit narrow expression patterns, these results demonstrate that Flp- and Cre-based Brainbow systems can be used in combination.

**Brainbow adeno-associated viral vectors**

In parallel to developing Brainbow transgenic lines, we generated adeno-associated viral (AAV) vectors to provide spatial and temporal control over expression and to make the method applicable to other species. Because the Brainbow 3.1 cassette described above is >6 kilobase pairs (kb), but the capacity of AAV vectors is <5 kb, we re-engineered the cassette. On the basis of results from initial tests (Supplementary Fig. 8), we devised a scheme in which \textit{loxP} sites with left or right element mutations\textsuperscript{44} were used for unidirectional Cre-dependent inversion (Fig. 5a,b). Farnesylated XFPs were positioned in reverse orientation to prevent Cre-independent expression, and WPRE elements were added to increase expression. In this design, recombination can lead to three outcomes from two XFPs: XFP1, XFP2 or neither. We generated two AAVs with two XFPs each, such that co-infection would lead to a minimum of eight hues (3 \times 3 – 1; Fig. 5c). Because AAV can infect cells at high multiplicity, the number of possible colors is \(\gg 8\). An additional feature is that excision of the non-expressed XFP in a second step (Fig. 5a) enhances and equalizes expression of the remaining XFP (Fig. 5d,e).

We infected cortex, cerebellum and retina of Cre transgenic mice with these vectors. When examined 3–5 weeks later, neurons were labeled in multiple colors (Fig. 5f–j and Supplementary Video 3). Near injection sites, high levels of infectivity led to coexpression of all XFPs in single cells so that neurons appeared gray or white. The variety of colors increased with distance from these sites and then decreased again in sparsely injected regions, presumably because each labeled neuron received only one virion (Supplementary Fig. 9).

**Methods to optimize Brainbow imaging**

Obtaining high-quality images from of tissues expressing Brainbow transgenes is challenging. Because colors are derived by mixing images of multiple fluorophores over a wide range of concentrations, factors that differentially affect the labels degrade the final image. In addition, it is usually necessary to image a tissue volume rather than a single section, so methods for taking image stacks must be optimized. Here we summarize guidelines for imaging Brainbow tissue.

**Sample preparation.** To minimize background, section thickness should be less than the working distance of the objective, generally <100 \(\mu\)m for high–numerical aperture (high NA) lenses. It is also important to match the refractive indices of the immersion medium and the sample because chromatic aberrations caused by mismatches between these values lead to spatial offsets between color channels (Supplementary Fig. 10). Commercial antifade...
mountants such as Vectashield (Vector Labs) or ProLong Gold (Invitrogen) that have refractive indices of ~1.47 are optimal for objectives that use glycerin as the immersion medium. Polyvinyl alcohol mountants (such as Mowiol 4-88; Sigma-Aldrich) provide a better match for oil-immersion (refractive index of ~1.52) objectives.

Confocal laser scanning microscopy. Epifluorescence microscopy can be used for imaging thin sections (<10 μm) or monolayer cultures, but confocal microscopes are preferable for thick specimens because they decrease contamination by light from outside the plane of focus. Newly developed two-photon multi-XFP imaging techniques are also useful. Apochromatic or fluoro microscope objectives that are corrected for three or more colors are strongly recommended. Most lens manufacturers specify preferred oils and coverslips. Using the wrong oil or coverslip degrades the sharpness of focus and increases chromatic aberration.

Fluorophores with overlap in the excitation or emission spectra should be imaged sequentially rather than simultaneously to minimize fluorescence cross-talk and thereby optimize color separation. Laser power should be set as low as possible for several reasons. First, all planes are bleached as each image plane is scanned, so generation of stacks leads to gradual bleaching and decreased signal through the stack. Second, because each fluorophore bleaches at a different rate, colors may shift during imaging. Third, linear signaling requires that fluorophores emit photons at submaximal rates; at higher excitation intensities, only the out-of-focus signal is increased. Fourth, if one fluorophore species is saturated but another is not, small changes in laser power will affect the fluorophore intensities differently, leading to color change. With high-NA objectives, a laser power of just a few milliwatts is saturating; this is generally a small percentage of the total power the laser can provide.

With laser power adjusted to a low level, the photomultiplier-tube voltages and digital gains must be set to relatively high values. In some confocal microscopes it is possible to compensate for signal loss from deep layers through automatic adjustment of laser power, photomultiplier-tube voltage or digital gain as a function of depth. Imaging parameters can be adjusted to obtain images with similar signal ranges throughout the stack.

Image processing. Brainbow images must be postprocessed to maximize color information, but care is needed to avoid introducing artifacts. Often one begins by reducing noise. Because confocal laser scanning of multicolor stacks is generally done at speeds of ~1 μs per pixel or less to save time, the number of photons collected for each pixel gives rise to sufficient shot noise to cause perceptible local color differences. This problem can be minimized by slower scanning or averaging of multiple scans, but when this is infeasible, simple filtering and deconvolution methods are helpful (Fig. 6a–c). For example, median or Gaussian filters with radii of 0.5–2 pixels reduce color noise, but at the expense of resolution. Deconvolution algorithms (Online Methods) are more challenging to use than simple filters but can remove color noise without compromising spatial resolution (Supplementary Fig. 11). Subsequent processing steps can expand the detectable color range and correct for color shifts (Fig. 6d,e). To obtain easily perceived color differences, pixel intensity values for each channel in each image are normalized to the same minimum and maximum intensity values for that color in the whole image stack. This linearly stretches all channels and images to the full dynamic range. Color shifts also arise because illumination strength is generally uneven across the imaging field and differs among lasers. This effect can be attenuated by intensity or shading correction for each channel. The resulting composite RGB images provide maximum color separation for viewing by eye (Fig. 6f).

DISCUSSION

The goal of the work reported here was to design, generate and characterize improved reagents for multicolor Brainbow imaging of neurons in mice. First, we generated new transgenic lines that overcome some limitations of the Brainbow 1 and 2 lines that are currently available. The improvements were the substitution of XFPs (especially red and orange fluorescent proteins)
that are more photostable and less prone to aggregation than those used initially; use of XFPs with minimal sequence homology so they could be immunostained separately; farnesylation of the XFPs for even staining of somata and the finest processes; insertion of a stop cassette to increase color variety by eliminating broad expression of a default XFP; inclusion of a nonfluorescent marker in the default position to facilitate screening of multiple lines; and insertion of a WPRE to boost expression (Figs. 1 and 2). These lines, which incorporate regulatory elements from the Thy1 gene, enable marking of many but not all neuronal types. To date, elements tested other than those from the Thy1 gene do not support the high expression levels needed to image Brainbow 1 and 2 material. The ability to immunostain provided by Brainbow 3 cassettes may allow weaker promoters to be used.

Second, we designed two additional transgenes and performed initial tests to demonstrate that they can be used effectively in vivo.
One construct, called Autobow, incorporates a self-excising Cre recombinase. Autobow lacks the temporal and spatial control afforded by the use of specific Cre lines or ligand-activated Cre (CreER). However, because it does not require the generation of double transgenics, it may be useful for rapid screening of neuronal morphology in mutant mice or mice submitted to various experimental interventions (such as drug treatments). The other novel transgene, Flpbow, replaces 

\[ \text{loxP} \] 

sites with 

\[ \text{FRT} \] 

and 

\[ \text{FRT} \] 

lines with distinct, defined specificities, it should be possible to map separate sets of neurons in a single animal.

Finally, we generated Brainbow AAV vectors. These, along with recently described Brainbow herpes viral vectors\(^5\), may be more useful than Brainbow transgenic mice in some situations. Similar to Autobow, they avoid the need for double-transgenic animals. Because the time of infection can be varied, these vectors provide an alternative to CreER for temporal control. Moreover, localized delivery of AAVs enables the tracing of connections from specified inputs to target brain areas.

The three most broadly useful Brainbow 3 lines (Brainbow 3.0 line D, Brainbow 3.1 line 3, Brainbow 3.1 line 18 and Brainbow 3.2 line 7) have been provided to Jackson Laboratories (\[\text{http://www.jax.org/}\); stock numbers 21225–21227) for distribution. The two AAVs shown in Figure 5 can be obtained from the University of Pennsylvania Vector Core (\[\text{http://www.med.upenn.edu/gtp/vectorcore/}\]). Plasmids used to generate Brainbow 3.0, 3.1, and 3.2, Autobow and Flpbow 1.1 and 3.1 mice are available through Addgene (\[\text{http://www.addgene.org/}\]).

**METHODS**

Methods and any associated references are available in the online version of the paper.

**Accession codes.** Addgene plasmids: 45176, 45177 (Brainbow 3.0), 45178 (Brainbow 3.1), 45179 (Brainbow 3.2), 45182, 45187 (Autobow), 45180 (Flpbow 1.1), 45181 (Flpbow 3.1).

*Note: Supplementary information is available in the online version of the paper.*

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**AUTHOR CONTRIBUTIONS**

B.C., K.B.C. and T.L. performed experiments. D.C., J.W.L. and J.R.S. designed experiments, interpreted results and wrote the manuscript.

**COMPETING FINANCIAL INTERESTS**

The authors declare no competing financial interests.
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ONLINE METHODS

Brainbow constructs. cDNA encoding the following fluorescent proteins were used: EGFP, EYFP, ECFP, mCherry, mKate2, PhaYFP (Evrogen), mTFP (Allele Biotechnology), TagBFP (Evrogen), EBFP2 (Addgene), Kusabira-Orange, TagRFPt, mOrange2 (Evrogen), tdTomato (Evrogen), and eqFP650 (Evrogen). A HRAS farnesylation sequence was added to tether XFPs to the cell membrane. A nuclear localization signal (NLS, APKKKRKV) was added to the N-terminal end of PhaYFP(Y65A). WPRE sequence was used to stabilize mRNA and enhance nuclear mRNA export. Polyadenylation signals were from the SV40 T antigen for mouse transgenes and from the human growth hormone gene for AAV. Brainbow constructs were assembled by standard cloning methods. A cloning scaffold containing concatenated iloxP mutant sequences and unique restriction digestion sites was synthesized (DNA2.0, Inc.) to facilitate cloning.

Brainbow modules were cloned into the pCMV- N1 mammalian expression vector (Clontech) for transient mammalian cell expression. Brainbow mouse constructs were cloned into a unique XhoI site in a genomic fragment of Thy1.2 containing neuron-specific regulatory elements. Brainbow AAV constructs were cloned into vectors provided by the University of Pennsylvania Viruse Core. Constructs were tested by expression in HEK293 cells (ATCC) before generation of mice or AAV.

Mice. Transgenic mice were generated by pronuclear injection at the Harvard Genome Modification Core. Mice were maintained on C57B6 or CD-1 backgrounds. Brainbow mice were crossed to mice that expressed Cre or Flp recombinases, including PV-Cre, Islet-Cre, CAGGS-CreER, L7-Cre, ChAT-Cre, Thy1-Cre, Wnt-Flp, and Actin-Flp. Both male and female mice were used. All experiments conformed to NIH guidelines and were carried out in accordance with protocols approved by the Harvard University Standing Committee on the Use of Animals in Research and Teaching.

AAV injection. Two Brainbow AAVs were mixed to equal titer (7.5 × 10^12 genome copies per ml) before injection. For retina injection, adult mice were anesthetized with ketamine-xylazine by intraperitoneal injection. A small hole was made in the temporal eye by puncturing the sclera below the cornea with a 30 1/2–G needle. With a Hamilton syringe with a 33-G blunt-ended needle, 0.5–1 µl of AAV virus was injected intravitreally. After injections, animals were treated with Antisedan (Zoetis) and monitored for full recovery. For cortex injection, adult mice were anesthetized with isoflurane via continuous delivery through a nose cone and fixed to a stereotaxic apparatus. Surgery took place under sterile conditions with the animal lying on a heating pad. One microliter of a 1:5 saline-diluted AAV mix (1.5 × 10^12 genome copies per ml) was injected over 10 min. The head wound was sutured at the end of the experiment. 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Antibodies. Expression vectors were constructed to produce His tag fusions of XFPs in Escherichia coli. Proteins were produced in bacteria, purified using His Fusion Protein Purification Kits (Thermo Scientific), concentrated to >3 mg/ml, and used as immunogens to produce rat anti-mTFP, chicken anti-EGFP, rat anti-PhiYFP, rabbit anti-mCherry and guinea pig anti-mKate2. Chicken anti-EGFP IgY was purified from chicken egg yolks using Pierce Chicken IgY Purification Kit (Thermo Scientific). Other sera were used without purification. Other antibodies used were: rabbit anti-GFP (ab6556, Abcam), rabbit anti-mTFP (AB604, Evrogen), chicken anti-SUMOstar (AB7002, LifeSensors), DyLight 405-conjugated goat anti-rat (Jackson ImmunoResearch) and Alexa fluorescent dye-conjugated goat anti-rat 488, anti-chicken 488 and 594, anti-rabbit 514 and 546, and anti–guinea pig 647 (Life Technologies).

Histology. Mice were anesthetized with sodium pentobarbital before intracardiac perfusion with 2%–4% paraformaldehyde in PBS. Brains were sectioned at 100 µm using a Leica v1000s vibrotome. Muscle and retina were sectioned at 20 µm in a Leica CM1850 cryostat or processed as whole mounts. For immunostaining, tissues were permeabilized by 0.5% Triton X-100 with 0.02% sodium azide in StartingBloc (Thermo Scientific) at room temperature for 2 h and then incubated with antibodies for 24–48 h at 4 °C. After extensive washing in PBST (0.01 M PBS with 0.1% Triton X-100), all secondary antibodies were added for 12 h at 4 °C. Finally, sections and tissues were mounted in Vectashield mounting medium (Vector Labs) and stored at −20 °C until they were imaged.

Antibody combinations used in figures are as follows. In Figures 1e–h; 2b–d; g and 4c and Supplementary Figures 2a–d, 4a and 5, primary antibodies are chicken anti-GFP (1:2,000), rabbit anti-mCherry (1:1,000, for mOrange2) and guinea pig anti-mKate2 (1:500). Secondary antibodies are Alexa dye-conjugated goat anti-chicken 488, anti-rabbit 546, and anti–guinea pig 647. In Figure 3b–d and Supplementary Figure 2e, primary antibodies are chicken anti-GFP (for ECFP), rabbit anti-PhiYFP (1:1,000) and guinea pig anti-mKate2. Secondary antibodies are Alexa dye-conjugated goat anti-chicken 488, anti-rabbit 546 and anti–guinea pig 647. In Figure 4b, rabbit anti-PhiYFP and Alexa dye-conjugated goat anti-rabbit 488 and anti-rabbit 546 and anti–guinea pig 647. In Figure 5d, primary antibodies are rat anti-mTFP and rabbit anti-mCherry. Secondary antibodies are Alexa dye-conjugated goat anti-rabbit 488 and anti-rabbit 546. In Figure 5f–j and Supplementary Figure 9, primary antibodies are guinea pig anti-mKate2 (for TagBFP), rat anti-mTFP (1:1,000), chicken anti-GFP (for EYFP) and rabbit anti-mCherry. Secondary antibodies are Alexa dye-conjugated goat antirabbit 488, anti-chicken 488, anti-rabbit5 46 and anti–guinea pig 647. In Supplementary Figure 1, primary antibodies are rat anti-PhiYFP (1:1,000) and rabbit anti-mCherry (1:1,000, for mOrange2). Secondary antibodies are Alexa dye-conjugated goat anti-rat 488 and anti-rabbit 546. In Supplementary Figure 7, primary antibodies are rabbit anti-EGFP (1:1,000, for ECFP) and chicken anti-SUMOstar (1:1,000). Secondary antibodies are Alexa dye-conjugated goat anti-rabbit 514 and anti-chicken 594.

Imaging. Fixed brain and muscle samples were imaged using a Zeiss LSM710 confocal microscope. Best separation of multiple fluorophores was obtained by using a 405-nm photodiode laser for TagBFP and Dylight 405, a 440-nm photodiode laser for mTFP, a 488-nm Argon line for EGFP and Alexa 488, a 514-nm
Argon line for EYFP and Alexa 514, a 561-nm photodiode for mOrange2 and Alexa 546, a 594-nm photodiode for mCherry, mKate2 and Alexa 594 or a 633-nm photodiode for Alexa 647. Images were obtained with 16× (0.8 NA), and 63× (1.45 NA) oil objectives. Confocal image stacks for all channels were acquired sequentially, and maximally or 3D-view projected using ImageJ (NIH). Intensity levels were uniformly adjusted in ImageJ.

Optimal imaging for Brainbow 3 tissue used a Zeiss LSM710 with fixed dichroic mirror combinations of DM455+514/594 to reduce lag time between the two sequential scans. EGFP and mKate2 were excited by 458-nm and 594-nm lasers simultaneously, and fluorescence was collected at 465–580 nm in channel 1 and 605–780 nm in channel 2, respectively. In a subsequent scan, a 514-nm laser was used to excite mOrange2, and fluorescence was collected at 545–600 nm in channel 2. In the antibody-amplified samples, conjugated Alexa dyes normally produced much stronger fluorescence signal than XFPs. The Zeiss microscope we used was optimized for imaging the Alexa 488/546/647 combination. The fixed dichroic mirror was DM488/561/633. Alexa 488 and Alexa 647 were excited by 488-nm and 633-nm lasers simultaneously, and fluorescence was collected at 495–590 nm in channel 1 and 638–780 nm in channel 2, respectively. In the subsequent scan, a 561-nm laser was used to excite mOrange2, and fluorescence was collected at 566–626 nm in channel 2.

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