New Transgenic Reporters Identify Somatosensory Neuron Subtypes in Larval Zebrafish

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ABSTRACT: **To analyze somatosensory neuron diversity in larval zebrafish, we identified several enhancers from the zebrafish and pufferfish genomes and used them to create five new reporter transgenes. Sequential deletions of three of these enhancers identified small sequence elements sufficient to drive expression in zebrafish trigeminal and Rohon-Beard (RB) neurons. One of these reporters, using the *Fru.p2x3-2* enhancer, highlighted a somatosensory neuron subtype that expressed both the *p2rx3a* and *pkcα* genes. Comparison with a previously described *trpA1b* reporter revealed that it highlighted the same neurons as the *Fru.p2x3-2* reporter. To determine whether neurons of this subtype possess characteristic peripheral branching morphologies or central axon projection patterns, we analyzed the morphology of single neurons. Surprisingly, although these analyses revealed diversity in peripheral axon branching and central axon projection, PKCα/*p2rx3a*/*trpA1b*-expressing RB cells did not possess obvious characteristic morphological features, suggesting that even within this molecularly defined subtype, individual neurons may possess distinct properties. The new transgenes created in this study will be powerful tools for further characterizing the molecular, morphological, and developmental diversity of larval somatosensory neurons.** Develop Neurobiol 73: 152–167, 2013

Keywords: **zebrafish; somatosensation; trigeminal; Rohon-Beard; peripheral axon; central axon; transgenic reporter**

INTRODUCTION

Somatosensation is carried out by a variety of specialized populations of sensory neurons that detect different types of thermal, chemical, and mechanical touch stimuli (Lumpkin and Caterina, 2007; Marmigère and Ernfors, 2007). Innervation of the skin by somatosensory neurons occurs very early in development, allowing animals to detect touch even at embryonic stages (Davies and Lumsden, 1984; Moore and Munger, 1989; Kimmel et al., 1990; Saint-Amant and Drapeau, 1998; Sagasti et al., 2005). The degree of heterogeneity among somatosensory neurons at early embryonic and larval stages has not been fully characterized, but distinct types of neurons can be

Additional Supporting Information may be found in the online version of this article.

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distinguished by both function and axon morphology. For example, *Xenopus* trigeminal neurons that innervate the head fall into two functionally, anatomically, and physiologically distinct types: Type I "movement" detectors inhibit swimming behavior, and their peripheral arbors have many fine branches with numerous large varicosities, whereas Type II "rapid transient" detectors stimulate behavior, and their peripheral arbors have few relatively straight branches with elongated varicosities (Roberts, 1980; Hayes and Roberts, 1983).

Zebrafish are an ideal model for studying early stages of somatosensory neuron development and function due to their external fertilization, rapid development, and optical clarity, but the heterogeneity of their embryonic and larval somatosensory neurons has not been well characterized. Zebrafish possess three populations of somatosensory neurons: trigeminal neurons that innervate the head, Rohon-Beard (RB) neurons that innervate the body at early larval stages, and dorsal root ganglia (DRG) neurons that innervate the body at later stages. Several observations suggest that embryonic and larval zebrafish possess multiple subtypes of somatosensory neurons. First, the cutaneous axons of trigeminal and RB neurons display a broad spectrum of peripheral axon branching patterns, which might reflect multiple subclasses with distinct morphologies (Sagasti et al., 2005). Second, populations of trigeminal peripheral axon arbors appear to "tile" the skin independently of one another: although the territories of all arbors are limited by repulsion, individual arbors only repel a subset of others (Sagasti et al., 2005). Third, distinct patterns of varicosities can be distinguished in the central axons of individual classes of trigeminal neurons, likely reflecting distinct synaptic patterns (Pan et al., 2012). Fourth, electrophysiological and molecular analyses have revealed that sodium currents in different populations of RB neurons rely on different sodium channels (Pineda et al., 2006). Finally, several genes, such as *protein kinase C alpha* (*pkcα;* Slatter et al., 2005; Patten et al., 2007), the ATP-gated ion channel *p2rx3a* (Boué-Grabot et al., 2000; Norton et al., 2000; Appelbaum et al., 2007), and the chemosensory ion channel *trpA1b* (Caron et al., 2008; Pan et al., 2012) are expressed in subpopulations of zebrafish trigeminal and RB neurons. Nonetheless, coexpression between most of these molecules has largely not been examined, so these observations have yet to cohere into a clear picture of the diversity among these neurons.

Fluorescent transgenic reporters have made it possible to study somatosensory neurons in live zebrafish larvae. The most commonly used reporters for these neurons use enhancers cloned from genomic regions near the *islet1* and *islet2b* genes to drive expression of a fluorescent protein (Higashijima et al., 2000; Uemura et al., 2005; Pittman et al., 2008). These enhancers have generally been thought to drive expression in all zebrafish somatosensory neurons, although one report suggests that a transgenic line using an *islet1* enhancer may mark a subset of neurons (Pan et al., 2012). Although these reporters have been useful for characterizing sensory neuron development, their presumed pan-neuronal labeling limits their utility for studying sensory neuron subtypes. Furthermore, several of these reporters use the Gal4-VP16/UAS system, which amplifies expression and allows combinatorial versatility (Köster and Fraser, 2001), but also attracts methylation (Goll et al., 2009), leading to variegated expression. Fluorescence expression in subsets of somatosensory neurons has been achieved with reporters for *trpA1b* and *p2rx3b* that were made by recombining fluorescent proteins into bacterial artificial chromosomes (BACs) (Kucenas et al., 2006; Pan et al., 2012), but such reporters are rare, can be laborious to create, and their relation to other reporters has yet to be fully assessed.

To initiate a systematic analysis of subtype-specific transgenes, we have created several reporters using enhancers from neurotrophin receptors and ion channels. Defining enhancer sequences that control expression of these reporters could help identify transcriptional pathways regulating somatosensory neuron development. Subtype-specific transgenic reporters will also be useful tools for characterizing somatosensory neuron diversity. These new fluorescent reporters will make it possible to test whether different axon morphologies are optimized for specific somatosensory functions and to characterize neural circuitry controlling behavioral responses to touch stimuli.

MATERIALS AND METHODS

Fish Strains and Transgenic Lines

Embryos were raised at 28.5°C on a 14 h/10 h light/dark cycle. All experiments were approved by the Chancellor's Animal Research Care Committee at the University of California, Los Angeles.

Expression analysis of transgenes was performed in wild-type AB or *Gt(T2KSAG)*^{j1229a} (Burgess et al., 2009) fish. Stable transgenic lines were created with the Tol2 transposase system (Kawakami, 2004). Supporting Information Table 1 summarizes all the transgenic lines used in this study as well as the transgenes used for transient transgenesis. Although transgenic lines were not mapped,

Table 1 Enhancer Regions from the Zebrafish and Pufferfish Genomes Drive Reporter Expression in Somatosensory Neurons

Enhancer	Size (bp)	Origin	Expression
isl1(ss)	4200	Zebrafish	TG, RB, other neurons*
CREST3	868	Zebrafish	TG, RB, DRG*
trpA1a	5019	Zebrafish	TG, RB, lateral line
trkA	3939	Pufferfish	TG, RB*
trkB	4017	Pufferfish	TG, RB, other neurons
trkC	3936	Pufferfish	TG, RB, other neurons, muscle
p2x3-2	1620	Pufferfish	TG, RB, muscle*

Enhancer regions were isolated by cloning sequences upstream of the translational start site (ATG) of indicated genes (Enhancers) of indicated lengths (Size, in base pairs) from the genomes of either zebrafish or pufferfish (Origin). All sequences drove expression in trigeminal and Rohon-Beard neurons (TG and RB); most also drove expression in additional tissues, such as muscle and other neurons (Expression). Expression analysis of all transgenes was performed with transient transgenesis, as described in the text. In some cases, stable transgenic lines (*) verified expression specificity. Shaded rows indicate previously reported enhancers.

expression from all lines segregated in a Mendelian manner, indicating that they integrated into single genomic loci.

Cloning/Transgenes

Enhancer regions of somatosensory neuron-specific genes were amplified from genomic DNA of the zebrafish *Danio rerio* or the pufferfish *Fugu rubripes* by PCR (Table 1). These enhancer regions were initially cloned into Gal4:GFP-pBSK vectors by PCR amplification using primers with restriction sites incorporated into the flanking sequences. Subsequent subcloning and promoter dissection of these elements were performed using the Muliti-Site Gateway Cloning System (Invitrogen, 12537-023) in combination with the Tol2 Gateway System developed by the Chien Lab (Kwan et al., 2007). Briefly, genomic sequences were PCR amplified with primers containing attB sites and recombined into pDONR P4-P1R, creating 5′ DONR plasmids. The binomial elements, E1b:Gal4-VP16:pA,14XUAS:E1b and E1b:LexA-VP16:pA,4xLexAop:E1b, were cloned into pDONR 221 to make middle element vectors. Reporter genes, EGFP, mCherry, and KikGR, were cloned into pDONR P2R-P3 to make 3′ elements. Reporter transgenes were created by recombination of different sets of pDONR elements using LR Clonase II Plus (Invitrogen, 12538120). Reporter function of each transgene was tested by injection into wild-type embryos. PCR primers used for amplifying genomic fragments are listed in Supporting Information Table 2.

Transient Analysis of Reporter Transgenes and Confocal Imaging

Zebrafish embryos were injected at the one-cell stage with ~2 nL of 50 ng/μL plasmid DNA, raised in a 28.5°C incubator, and treated with phenylthiourea at 24 hpf to block pigmentation. Larvae were screened for fluorescence between 24 and 72 hpf using a Zeiss Discovery.V12 SteREO fluorescence dissecting scope.

For confocal imaging, fish were anesthetized with 0.02% tricaine and mounted in 1.2% low melt agarose (Promega, V2111). Fluorescence was imaged with a Zeiss LSM 510 confocal microscope using a 488-nm laser line for GFP/YFP/Citrine, 633 nm for Cy5, and 543 nm for mCherry/DsRed/rhodamine. Images were taken with a 20× water objective (a 0.7× or 2× optical zoom was used where indicated) and projected from 20 to 50 optical sections of ~3 μm intervals.

Photoconversion of KikGR Protein

Photoconversion of KikGR protein was performed using a Discovery.V12 SteREO fluorescence dissecting scope with a UV filter. Larvae were exposed to UV light for 5 min or until all neurons were photoconverted from green to red. Neurons were photoconverted in 24-h intervals, subsequent to confocal imaging. Photoconverted larvae were raised at 28.5°C, in the dark, until imaging the following day.

Morphological Analysis of Peripheral Axons

High-resolution (1024 × 1024 pixels) confocal images of single neurons were collected as described earlier. Using NeuroLucida tracing software, axons were traced in three dimensions; the primary axon projecting from the cell body to the first branch point in the skin was excluded from the analysis. Branch length and number for each traced neuron were acquired using NeuroLucidaExplorer software and analyzed with a Matlab program, which is described in detail in Supporting Information.

Retrograde Labeling of Mauthner Cells

Retrograde labeling of Mauthner cells was performed using rhodamine dextran (Invitrogen, 1824) according to established protocols (Fetcho and O'Malley, 1995; Volkmann and Köster, 2007). A filamented glass needle filled with a saturated concentration of rhodamine dextran was used to create a lesion and introduce the dye within the caudal spinal cord of 48 hpf larvae. Larvae were allowed to recover for at least 24 h at 28.5°C, in the dark, before imaging.

Whole-Mount Double Fluorescent *In Situ* Hybridization and Antibody Staining

Embryos were fixed in 4% paraformaldehyde overnight at 4°C and permeabilized with proteinase K before antibody staining and/or *in situ* hybridization with standard protocols (Boué-Grabot et al., 2000; Slatter et al., 2005; https://wiki.zfin.org/display/prot/Thisse+Lab+-+In+Situ+Hybridization+Protocol+-+2010+update). Antibody staining was performed with primary antibodies (PKCα, GFP/YFP/Cit-

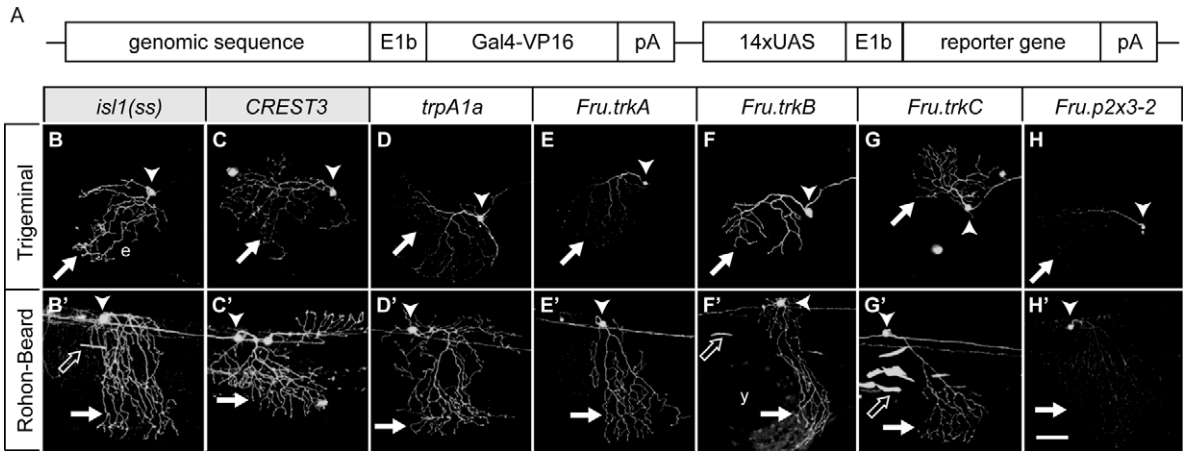

Figure 1 New transgenes drive expression in zebrafish somatosensory neurons. A: Design of transgenic reporters: genomic sequences containing somatosensory-specific enhancers drove the Gal4-VP16 transcriptional activator; on the same plasmid, 14 copies of the Gal4 upstream activation sequence (14xUAS) were used to drive GFP. The adenovirus E1b minimal promoter was placed upstream of both Gal4-VP16 and the reporter gene. An SV40 polyadenylation sequence was placed 3′ to both Gal4-VP16 and the reporter gene to signal transcription termination. B–H′: Transgenes were transiently expressed in zebrafish larvae and imaged by confocal microscopy at 72 hpf. Both zebrafish and pufferfish (Fru) genomic enhancer sequences drove expression of fluorescent reporters in zebrafish trigeminal (B–H) and Rohon-Beard (B′–H′) neurons. Anterior is left, and dorsal is up in all images. The eye (e) and yolk (y) are indicated. Arrowheads point to cell bodies; arrows point to peripheral arbors; empty arrows point to muscle. Scale bar, 100 μm.

rine and mCherry; 1:500) incubated overnight at 4°C followed by incubation with AlexaFluor secondary antibodies (488 anti-mouse and 568 anti-rabbit for GFP, YFP and citrine-expressing transgenics or 568 anti-mouse and 488 anti-rabbit for mCherry-expressing transgenics; 1:1000) at 4°C overnight (Supporting Information Table 3). Specificity of the PKCα antibody staining was verified with coexpression analysis, as shown in Figure 5. Supporting Information Table 3 summarizes the antibodies used in this study. For fluorescent *in situ* hybridization (FISH), embryos were incubated with DIG-labeled riboprobe (*p2rx3a* or *trkA*) and visualized using Cy5-tyramide amplification (1:100; Perkin Elmer, NEL752001KT). Embryos were mounted dorsally and imaged using confocal microscopy, as described earlier.

RESULTS

Zebrafish and Pufferfish Genomic Sequences Drive Transgene Expression in Trigeminal and RB Neurons

To analyze the development and diversity of somatosensory neurons in larval zebrafish, we created a library of transgenic reporters by cloning zebrafish (*Danio rerio)* and pufferfish (*Fugu rubripes*) genomic regions from upstream of neurotrophin receptors and ion channels (ATP-gated channels and Trp channels) and used them to drive expression of GFP (Table 1, Fig. 1). To ensure robust reporter expression and allow for potential coexpression of effector genes, these candidate enhancers were subcloned upstream of the Gal4-VP16 transcriptional activator; on the same plasmid, multiple copies of the Gal4 upstream activation sequence (14xUAS) were used to drive GFP expression [Fig. 1(A)]; (Köster and Fraser, 2001). For comparison, we also created similar transgenes using two previously identified somatosensory-specific enhancers from the *islet1* gene, *isl1(ss)*, and *CREST3* (Higashijima et al., 2000; Uemura et al., 2005). Similar to the *islet1* enhancers, several of the cloned candidate sequences (from the *trpA1a*, *Fru.trkA*, *Fru.trkB*, *Fru.trkC* and *Fru.p2x3-2* genes) drove GFP expression primarily in zebrafish trigeminal [Fig. 1(B–H)] and RB [Fig. 1(B′–H′)] neurons. Many of these reporters were also consistently expressed in limited populations of additional cells, including muscles or other populations of neurons (Table 1). Stable transgenic reporter lines using several of these enhancers (*isl1(ss)*, *CREST3*, *Fru.trkA*, and *Fru.p2x3-2*) exhibited similar patterns of fluorescence, confirming the reliability of the transient transgenic approach for characterizing expression.

Using transient transgenesis, we analyzed the onset of fluorescence in somatosensory neurons to determine whether these reporters exhibited differences in

temporal expression. The zebrafish *isl1(ss)* enhancer drove expression earliest, turning on approximately at the 13 somites (som) stage, before somatosensory neurons have projected central and peripheral axons. Expression from *CREST3* and *trpA1a* enhancer-driven reporters was first visible at the 17 somites stage, *Fru.p2x3-2* enhancer-driven expression began at the 20 somites stage, *Fru.trkA* enhancer-driven expression began at 28 h postfertilization (hpf), and *Fru.trkC* enhancer-driven expression began at 30 hpf [Fig. 2(A)].

Determining when enhancer activity ceased was more difficult than determining when it turned on, because mRNA and proteins can perdure for many hours. We devised a technique using a photoconvertible fluorescent protein to address this issue and used it to characterize *isl1(ss)* and *CREST3* enhancer activity. Stable transgenic lines were made using these enhancers to drive expression of KikGR, a photoconvertible fluorescent protein that changes from green to red when exposed to UV light (Tsutsui et al., 2005). KikGR-expressing cells were photoconverted and imaged at daily intervals [Fig. 2(B)]. Expression of green fluorescence after photoconversion indicated newly synthesized KikGR; absence of green fluorescence after photoconversion indicated that the enhancer had turned off. With this approach, we found that the *isl1(ss)* enhancer drove expression until ~54 hpf [Fig. 2(C–G)], while the *CREST3* enhancer continued to be active past 13 days post-fertilization (dpf) in a subset of somatosensory neurons [Figs. 2(C′–G′) and 3(A)].

Small Regulatory Regions Were Sufficient for Transgene Expression in Zebrafish Somatosensory Neurons

Identifying smaller genomic regions sufficient to drive expression in somatosensory neurons could make enhancers easier to subclone, potentially improve expression specificity or efficiency, and makes possible the identification of conserved regulatory motifs. To isolate minimal sequences sufficient for somatosensory neuron expression, we performed sequential deletion analysis of the *Fru.trkA*, *Fru.p2x3-2*, and *trpA1a* enhancer regions. Specific regions from within each enhancer sequence were subcloned into fluorescent reporter transgenes [Fig. 4(A)], which were then injected into one-cell stage embryos and monitored for transient expression during the first 3 days of development. To estimate the relative efficiency of each enhancer, we quantified the number of embryos with fluorescence in somatosensory neurons in each injected clutch (Fig. 4).

From an initial ~4 kb [−3939: −1] *Fru.trkA* enhancer region, we isolated a ~1 kb region proximal to the start site [−996: −1] capable of driving expression in somatosensory neurons [Fig. 4(B)]. This enhancer was almost twice as efficient as the original ~4 kb sequence (48% vs. 25% of embryos with expression), indicating that there may be a negative regulatory element within the distal 3 kb of the original enhancer that reduced its activity. Subsequent deletions within the [−996: −1] fragment decreased its efficiency, with the two shortest sufficient elements [−996: −814] and [−238: −81] driving expression in an average of ~18 and 20% of embryos, respectively. However, when these two minimal regions [−996: −814] and [−238: −81] were combined [−996: −678, −238: −1], they were almost as efficient as the [−996: −1] fragment, indicating that each of the two small regulatory elements were sufficient for somatosensory expression, but summed to achieve optimal expression.

The ~1.6 kb [−1619: −1] *Fru.p2x3-2* enhancer was dissected into several progressively smaller fragments that drove expression in TG and RB neurons [Fig. 4(C)]. One of these fragments was 305 bp long [−1036: −731] and drove expression with comparable efficiency to the full 1.6 kb sequence (65 and 70% of embryos, respectively). A 144 bp fragment [−946: −802] was also sufficient for expression in somatosensory neurons, but was less efficient.

Dissection of the ~5 kb [−4993: −1] *trpA1a* genomic sequence indicated that the ~2 kb furthest from the start site was sufficient to drive expression [Fig. 4(D)]. By examining overlapping fragments, we isolated a 941 bp region [−4457: −3517] that was sufficient for expression in somatosensory neurons. However, partially overlapping fragments [−4993: −4003] and [−3873: −3013] were unable to drive expression, indicating that multiple elements are required together. By creating four internal deletions of this 941 bp [−4457: −3517] fragment, we found two smaller regions [−4136: −3946] and [−3946: −3517] that were required but not sufficient to drive robust expression in sensory neurons.

The *Fru.p2x3-2* Reporter and PKCα Gene Trap Reporter Define a Somatosensory Neuron Subset That Partially Overlaps with Neurons Expressing a *Fru.trkA* Reporter

PKCα is expressed in ~40% of RB neurons in 24 and 48 hpf larvae (Slatter et al., 2005). We obtained a gene trap line with an insertion in the gene-encoding

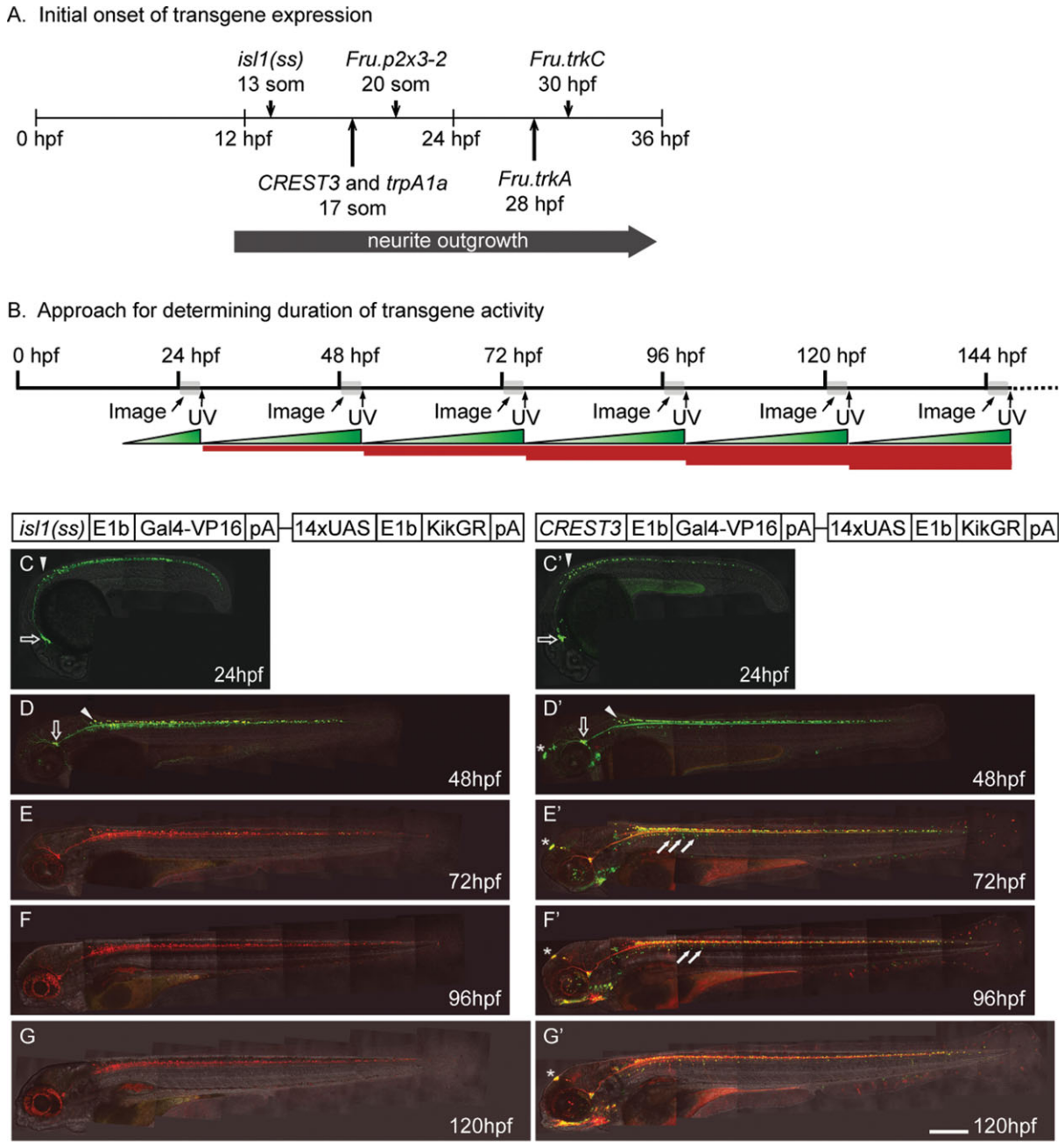

Figure 2 Different transgenes have distinct temporal expression patterns. A: Onset of gene expression as determined by transient transgenesis. Transgenes with indicated enhancers driving GFP (see Fig. 1) were injected into embryos at the one-cell stage. Embryos were raised at 28.5°C and staged according to somite (som) number and hours postfertilization (hpf). Initial observation of GFP expression was recorded. Expression driven by the *isl1(ss)* enhancer was the earliest at 13 som, followed by *CREST3* and *trpA1a* enhancer-driven expression at 17 som, *Fru.p2x3-2* enhancer-driven expression at 20 som, *Fru.trkA* enhancer-driven expression at 28 hpf, and *Fru.trkC* enhancer-driven expression at 30 hpf. B: The duration of *isl1(ss)* and *CREST3* enhancer activity was determined by daily photoconversion and imaging of KiKGR expression. Green fluorescence indicated newly synthesized KikGR (active promoter, new neuron), red fluorescence indicated older/photoconverted KikGR (inactive promoter, old neuron), and yellow indicated neurons expressing both forms of KikGR (active promoter, old neuron). C–G: The *isl1(ss)* enhancer was active from 14 hpf until $\sim$ 54 hpf. C′–G′: Enhancer activity in sensory neurons lasted until at least 14 dpf (see Fig. 3). Confocal images were taken with a 20× objective and 0.7× optical zoom; anterior is left and dorsal is up. Empty arrows indicate the trigeminal ganglia, arrowheads point to anterior RB neurons, filled arrows are DRGs, and asterisks are located near a population of anterior neurons. Scale bar, 300 μm.

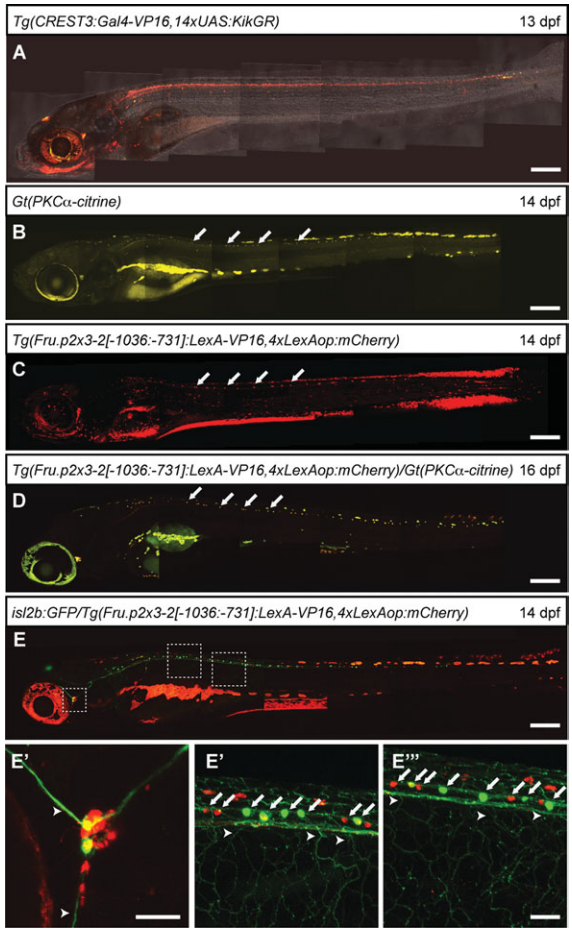

Figure 3 Rohon-Beard neurons persist in 2-week-old larvae. Somatosensory neurons in (A) *CREST3*, (B) *PKCα*^{ct7a}, (C) *Fru.p2x3-2*, (D) *Fru.p2x3-2*/*PKCα*^{ct7a}, and (E) *isl2b*/*Fru.p2x3-2* transgenic reporter fish were visible until at least 2 weeks post-fertilization. Confocal images were taken with a 20× objective; anterior is left and dorsal is up. E′–E‴: Magnified images of various regions outlined in (E). Trigeminal neurons are shown in (E′) and RB neurons in (E″) and (E‴). Arrows point to individual RB neuron cell bodies. Arrowheads in (E′–E‴) point to RB neuron peripheral arbors. Scale bar, 200 μm in (A–E) and 50 μm in (E′–E‴).

PKCα (*PKCα*^{ct7a}) to examine the relationship between the neurons marked by our reporter lines and PKCα-expressing neurons. In this line, an exon encoding the yellow fluorescent protein, citrine, is integrated between exons 3 and 4 of the PKCα gene, resulting in the expression of a PKCα-citrine fusion protein under the control of the endogenous PKCα transcriptional regulatory elements (Trinh et al., 2011). To determine if expression from *PKCα*^{ct7a} is confined to a subset of RB neurons, we crossed it to an *isl1(ss)* transgenic reporter line, *Tg(isl1(ss):Gal4-VP16,14xUAS:DsRed)*. Because of variegation from the Gal4-VP16/UAS system, DsRed in this line is expressed in ∼74% of RB neurons (as determined by crossing it to a non-Gal4-VP16/UAS, nonvariegated *isl2b:GFP* line) [Fig. 5(A,F)]. At 72 hpf, 41% of RB neurons in the *isl1(ss)* reporter line also expressed citrine from the *PKCα*^{ct7a} gene trap line and 56% expressed DsRed only [Fig. 5(B,F)]. Three percent of the labeled neurons expressed citrine only, which likely represents a population of neurons with silenced DsRed.

The *p2rx3a* gene is also expressed in a subset of somatosensory neurons (Boué-Grabot et al., 2000; Norton et al., 2000; Appelbaum et al., 2007). To create a potential reporter line for the *p2rx3a* gene, we used the *Fru.p2x3-2* enhancer (P3X3-2 is the pufferfish holomog of zebrafish P2rx3a) to drive expression of LexA-VP16 and drove expression of mCherry with the LexA operator (4xLexAop). Using the LexA-VP16/LexAop binary system has the same advantages as the Gal4-VP16/UAS system in terms of amplification and combinatorial versatility, but these lines can be crossed to Gal4-VP16/UAS lines without cross-activating them (Lai and Lee, 2006). Crossing a *Fru.p2x3-2* reporter line, *Tg(Fru.p2x3-2[-1036,-731]:LexA-VP16,4xLexAop:mCherry)*, to the *isl2b:GFP* line revealed that the *Fru.p2x3-2* reporter labeled ∼30% of RB neurons [Fig. 5(C,F)]. To determine the relationship between the *Fru.p2x3-2* reporter and *PKCα*^{ct7a} neurons, we crossed the two lines together [Fig. 5(D)]. Strikingly, citrine and mCherry expression almost completely coincided, with 96% of RB neurons expressing both [Fig. 5(F)]. Thus, an RB neuron subtype, comprising ∼30–40% of the population, is marked by expression of both the *Fru.p2x3-2* reporter line and *PKCα*^{ct7a}.

This subtype of RB neurons persists until at least 16 dpf [Fig. 3(B–E)], well beyond the time when RB neurons are thought to disappear, consistent with previous reports that PKCα-expressing RB neurons are present until at least 2 weeks postfertilization (Slatter et al., 2005; Patten et al., 2007). RB neurons in fish and amphibians degenerate during larval stages, and their function is replaced by DRG neurons. It has been reported that most (Williams et al., 2000; Svoboda et al., 2001) or at least a subset (Reyes et al., 2004) of RB neurons degenerate in zebrafish between 2 and 4 dpf. We did not detect widespread RB neuron degeneration within the first 5 days of development with any of our reporter transgenes and found that at least some RB neurons persisted for at least 2 weeks in several transgenic lines (Fig. 3). This observation is consistent with previous studies (Metcalfe et al., 1990; Slatter et al., 2005; Patten et al., 2007; O'Brien et al., 2012), suggesting that RB neuron degeneration

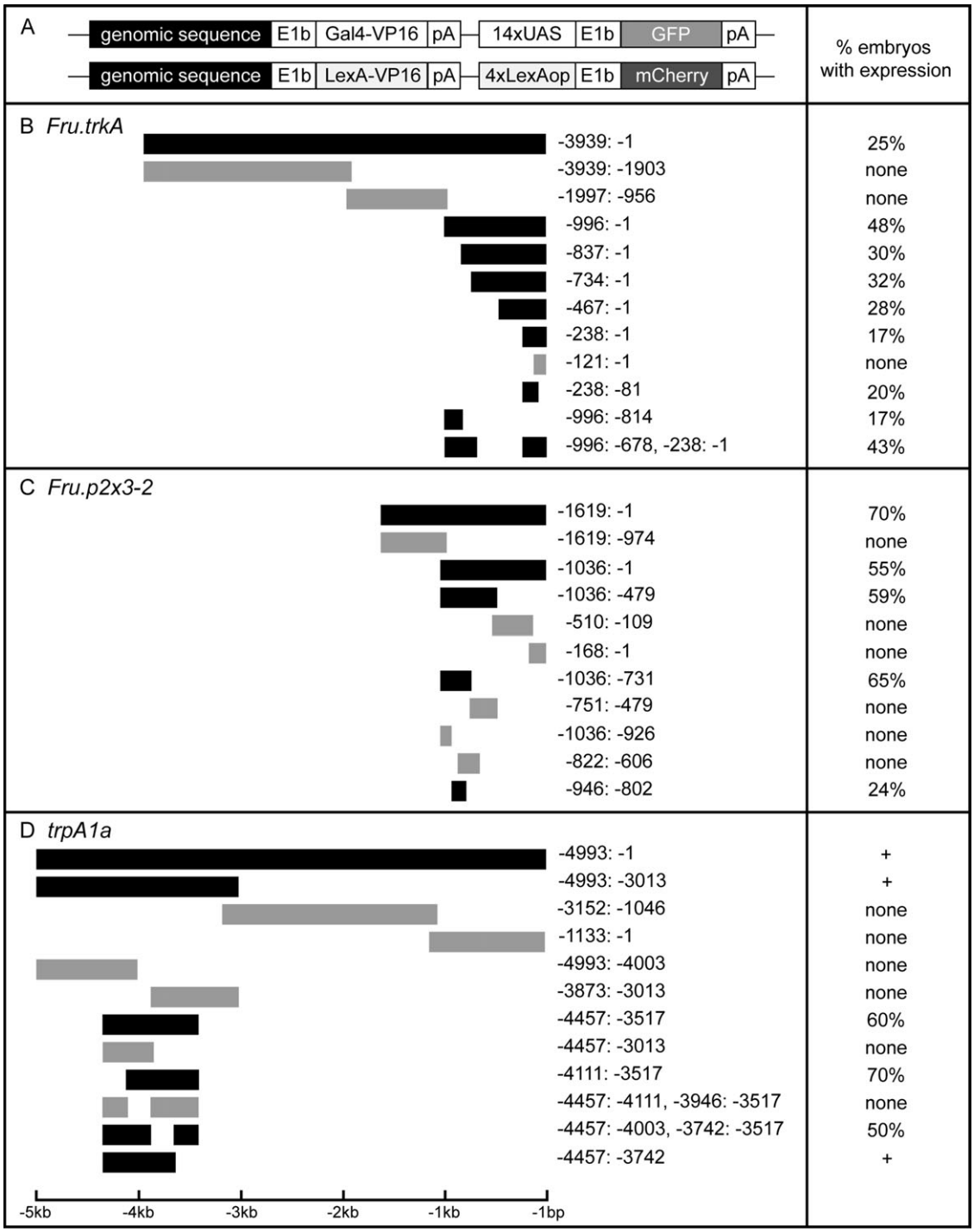

Figure 4 Identification of minimal regulatory elements sufficient for transgene expression in zebrafish trigeminal and Rohon-Beard neurons. A: Transgenes were constructed by cloning genomic sequences upstream of Gal4-VP16,14xUAS:GFP or LexA-VP16,4xLexAop:mCherry; the E1b promoter and SV40 pA sequence were used as indicated. B: Two fragments of the *Fru.trkA* enhancer, each less than 200 bp, were sufficient to drive expression in sensory neurons, although both together were required to drive expression at levels similar to the $\sim$ 1 kb fragment [−996: −1]. C: A 144 bp fragment [−946: −802] of the *Fru.p2x3-2* enhancer sequence was sufficient to drive expression in somatosensory neurons, although its efficiency was lower than that of a 305 bp fragment [−1036: −731]. D: The *trpA1a* enhancer sequence was divided into four functional elements. The right column indicates the percent of embryos with expression within a clutch. (+) in (D) indicates qualitatively similar expression from each transgene, although this was not quantitatively measured.

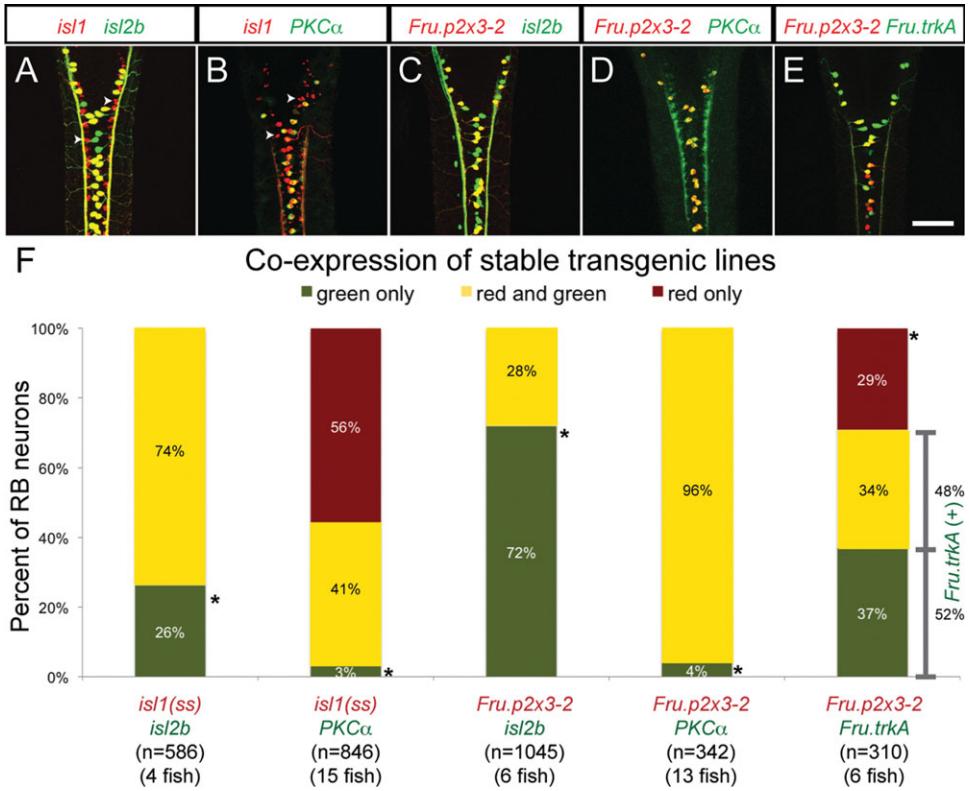

Figure 5 The PKCα^{ct7a} gene trap line and a transgenic reporter using a *Fru.p2x3-2* enhancer label the same subset of Rohon-Beard neurons. A–E: Transgenic lines, each using the indicated enhancers to drive expression of different fluorescent proteins, were crossed to compare their expression patterns. A: Crossing *Tg(isl1(ss):Gal4-VP16,14xUAS:DsRed)* to *Tg(-17.6isl2b:GFP)* allowed us to estimate the degree of variegation caused by the Gal4/UAS system: the *isl2b* (GFP) and *isl1(ss)* (DsRed) enhancers are thought to drive expression in all somatosensory neurons; however, the *isl1(ss)* reporter line was expressed in only 74% of *isl2b:GFP* RB neurons (coexpression shown in yellow), suggesting that in the *isl1(ss)* line, the Gal4/UAS system was silenced in ~ 25% of RB neurons. Small lateral DsRed-labeled cells are not RB neurons. B: The PKCα^{ct7a} line labeled ~ 40% the RB neurons labeled by the variegated *isl1(ss)* reporter line. C: The *Fru.p2x3-2* reporter line labeled approximately a third of all RB neurons labeled by *isl2b:GFP*. D: The *Fru.p2x3-2* reporter line was expressed in the same population of RB neurons as the PKCα^{ct7a} line. Note that the PKCα fusion protein is excluded from the nucleus. E: Approximately 50% of RB neurons labeled by the *Fru.trkA* reporter line overlapped with the *Fru.p2x3-2* reporter line. Dorsal confocal images were taken of the anterior spinal cord with a 20× objective; anterior is up. Scale bar, 100 μm. F: Quantification of coexpression between transgenic lines. *n* = total number of RB neurons. Asterisks indicate categories that may underestimate coexpression due to variegation in some reporter lines.

in zebrafish might be more limited or occur at later stages than previously thought.

Like the *p2rx3a* gene, the *trkA* gene is also expressed in a subpopulation of larval zebrafish somatosensory neurons (Martin et al., 1995; Pan et al., 2012). We hypothesized that reporters using the *Fru.trkA* enhancer would highlight this subtype, allowing us to assess its relationship to the *Fru.p2x3-2* reporter-expressing subpopulation. We made three *Fru.trkA* transgenes using the Gal4-VP16/UAS system and one using the LexA-VP16/LexAop system to drive expression of different reporter genes. All these lines were extensively variegated, but unfortunately, without the use of the amplification systems, expression from this enhancer was very weak (data not shown). A line using *Fru.trkA* to drive expression of a YFP-tagged version of the light-activated ChannelRhodopsin-2 (ChR2-YFP), *Tg(Fru.trkA:Gal4-VP16,14xUAS:ChR2-YFP)*, was the least variegated, so we crossed it to the *Fru.p2x3-2* reporter line [Fig. 5(E)]. Fluorescence expression in the *Fru.trkA* reporter line partially overlapped with the subset

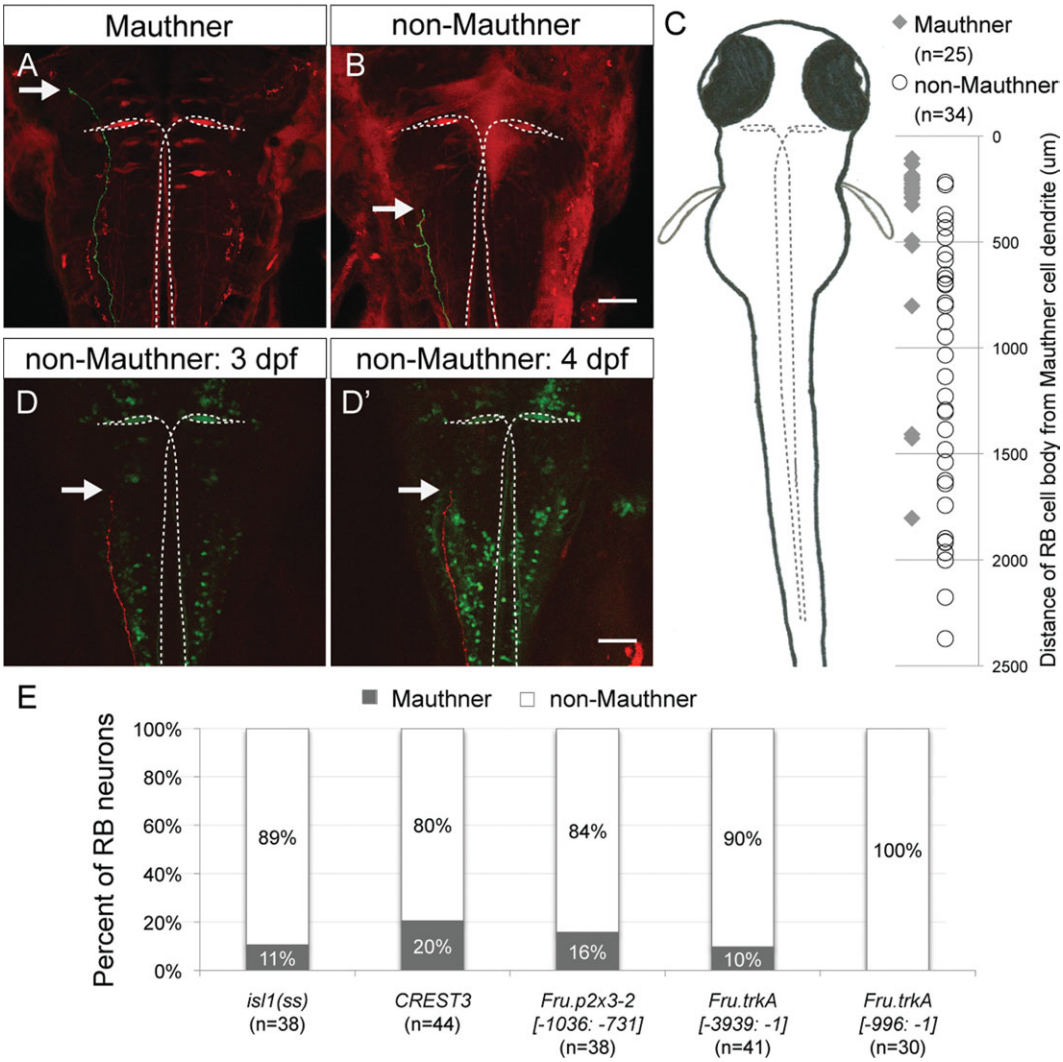

Figure 6 Rohon-Beard central projections either contact or fail to contact the Mauthner cell dendrite. A, B: Dorsal confocal images of 72 hpf larvae exhibit two patterns of central projection termination. Some RB central projections contacted the Mauthner cell dendrite (labeled by retrograde dye-filling) (Mauthner) (A), whereas others terminated caudal to the Mauthner cell dendrite (non-Mauthner) (B). Arrows indicate the rostral termini of RB central axons. The Mauthner cells are outlined. Scale bar, 50 μm. C: The position of a neuron's cell body along the rostral-caudal axis did not dictate whether or not its central projection contacted the Mauthner cell dendrite. D, D′: Failure to contact the Mauthner cell dendrite was not due to slow RB central axon growth. Confocal images of a non-Mauthner contacting RB neuron (red) in the *Gt(T2KSAG)*^{j1229a} gene trap line taken at 3 and 4 dpf. Scale bar, 50 μm. E: All transgenes primarily labeled non-Mauthner dendrite contacting RB neurons. n = total number of RB neurons.

labeled by the *Fru.p2x3-2* reporter line. Although variegation made it difficult to analyze neurons that were not labeled by the *Fru.trkA* reporter line, it was clear that only about half of the neurons expressing this reporter also expressed the *Fru.p2x3-2* reporter line, which is not highly variegated (see below), indicating that it marks a different, perhaps broader, set of neurons than the *Fru.p2x3-2/PKCα*^{ct7a} reporters [Fig. 5(F)].

Morphological Variation in Peripheral and Central Arbors of RB Neurons Does Not Correlate with Subtype Reporters

Having identified PKCα/*p2rx3a*-expressing RB neurons as a distinct subtype, we hypothesized that these neurons might display a characteristic peripheral axon branching morphology optimized for their sensory properties or a distinct central connectivity

pattern dictating their behavioral function. To test the former possibility, we examined confocal images of single neurons expressing different transgenic reporters (using the *isl1(ss)*, *Fru.trkA*, *Fru.trkC*, or *Fru.p2x3-2* enhancers) in 72 hpf transient transgenic embryos [Fig. 1(B′–H′)]. Peripheral arbors of neurons labeled by each transgene did not exhibit dramatically distinct morphologies, like those that distinguish sensory subtypes in *Xenopus* (Hayes and Roberts, 1983) or *Drosophila* (Grueber et al., 2003) larvae. However, to assess morphology more objectively, we manually traced arbors of many single neurons arborizing over the central trunk with NeuroLucida tracing software (MicroBrightField), allowing us to extract quantitative information about each arbor. To compare arbors, we created a Matlab program that generated a hierarchically clustered dendrogram reflecting the degree of morphological similarity between each pair of axons, based on branch length and number for each branch order. The algorithm reliably segregated most trigeminal and RB arbors into different groups and grouped arbors of the same neurons traced by different experimenters, giving us confidence that the method accurately distinguishes peripheral axons [Supporting Information Fig. 1(A,A′)]. This program segregated RB arbors into five major clusters, but neurons labeled by different transgenes fell into multiple clusters, indicating substantial morphological diversity within each population of RB neurons labeled by these transgenic reporters [Supporting Information Fig. 1(B–F)]. This quantitative analysis confirmed our qualitative impression that peripheral arbors marked by different transgenes do not exhibit dramatic morphological distinctions but does not preclude the possibility that other more subtle features could distinguish these arbors.

The central axons of somatosensory neurons connect to downstream neurons in the central nervous system to elicit behavioral responses. In zebrafish larvae, touch elicits a stereotypical C-start escape response (Saint-Amant and Drapeau, 1998; Drapeau et al., 2002). This response has been attributed to the direct activation of a well-characterized pair of reticulospinal interneurons that form in rhombomere 4 of the hindbrain, called Mauthner cells, by RB neurons (Korn and Faber, 2005; Kohashi and Oda, 2008). However, touch can elicit an escape response in the absence of the Mauthner cells (Liu and Fetcho, 1999; Burgess et al., 2009), or even the entire hindbrain (Downes and Granato, 2006), suggesting that RB neurons can connect directly to spinal cord circuits.

We hypothesized that subtypes of RB neurons might connect to distinct circuits, as has been suggested for trigeminal neurons (Pan et al., 2012). To characterize central axon projections of RB neurons, we imaged single neurons in transient transgenics while simultaneously visualizing the Mauthner cells by dye-filling (Fetcho and O'Malley, 1995; Volkmann and Köster, 2007) or with a transgenic line, Gt(T2KSAG)^{j1229a} (Burgess et al., 2009) [Fig. 6(A,B,D,D′)], respectively. Surprisingly, the central projections of most RB neurons failed to contact the Mauthner cell dendrite, instead terminating either in the caudal hindbrain or within the spinal cord [Fig. 6(B)]. Both Mauthner- and non-Mauthner dendrite-contacting neurons were situated all along the rostral-caudal extent of the spinal cord, although Mauthner dendrite-contacting RB neurons appeared to be more abundant in the rostral spinal cord [Fig. 6(C)]. Failure to contact the Mauthner dendrite was not due to delayed outgrowth, because these axons never grew further into the hindbrain [Fig. 6(D,D′)].

The majority of RB neurons labeled by all the examined transgenes (using the *isl1(ss)*, *CREST3*, *Fru.p2x3-2*, and *Fru.trkA* enhancers) failed to contact the Mauthner cell dendrite [Fig. 6(E) and data not shown]. Notably, neurons labeled by the *Fru.p2x3-2* reporter displayed a similar distribution of central axon termination patterns as neurons labeled by the *isl1(ss)* and *CREST3* enhancer-driven reporters, indicating that although PKCα/*p2rx3a*-expressing neurons define a distinct RB subtype, neurons within that subtype can exhibit different termination patterns.

Fluorescent Transgenes Reflect Endogenous Gene Expression

To determine whether the subpopulations of neurons identified with our reporters reflect endogenous gene expression and thus truly distinct molecular subtypes of somatosensory neurons, we examined endogenous protein or mRNA expression in our reporter lines (Fig. 7). Double antibody staining for PKCα protein and GFP in the *isl2b:GFP* line confirmed that PKCα-expressing neurons make up a subpopulation of RB neurons [Fig. 7(D,G)]. Staining for endogenous PKCα and for citrine in *PKCα*^{ct7a} verified that the gene trap line faithfully labels all PKCα-expressing RB neurons at 72 hpf [Fig. 7(A,G)]. As expected, PKCα and mCherry antibody staining in the *Fru.p2x3-2* reporter line, *Tg(Fru.p2x3-2[-1036, -731]:LexA-VP16,4xLexAop:mCherry)*, revealed that most PKCα-expressing neurons (89%) are labeled by the *Fru.p2x3-2* reporter line [Fig. 7(E,G)].

FISH for *p2rx3a* (previously reported as *p2x3*, *p2rx3*, and *p2x3.1*) and antibody staining for mCherry in 72 hpf *Tg(Fru.p2x3-2[−1036, −731]:LexA-*

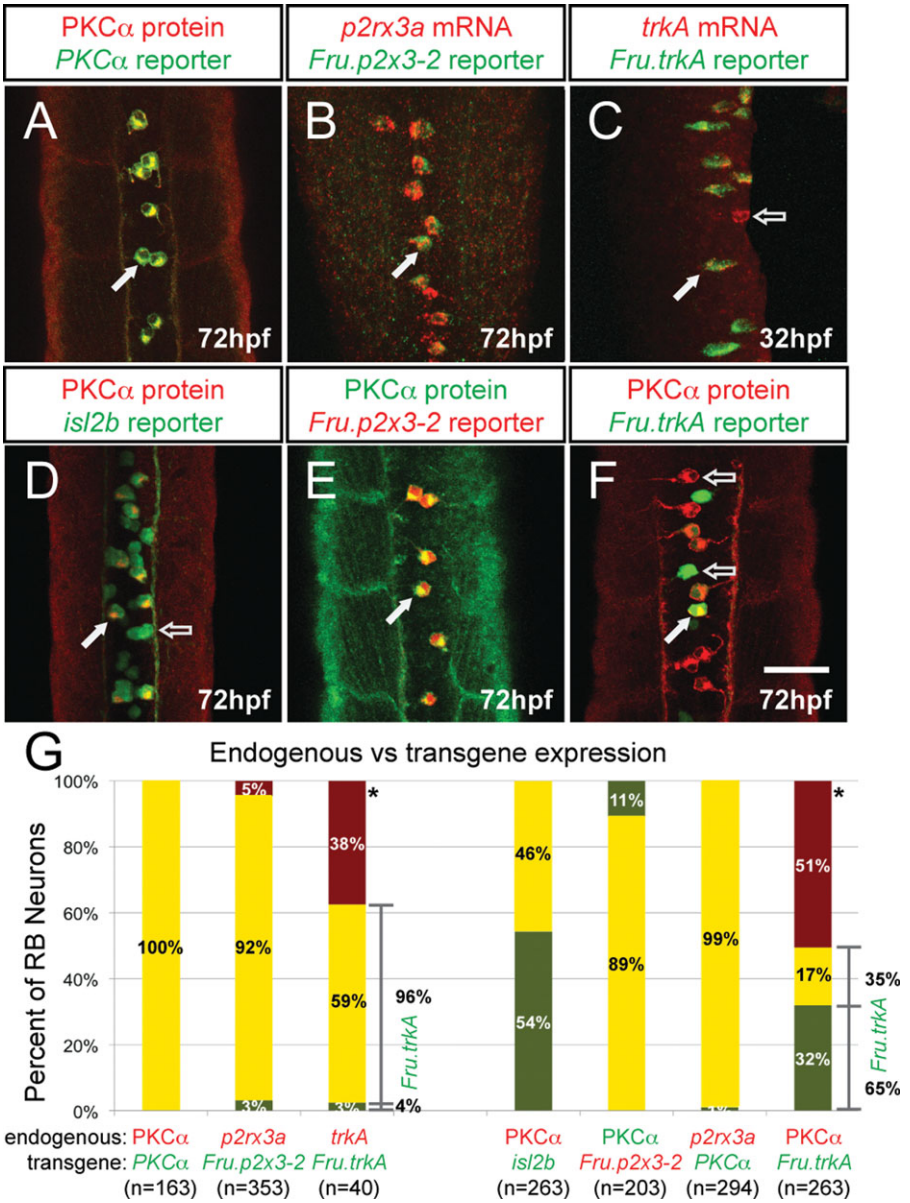

Figure 7 Fluorescent transgenic reporters accurately reflect endogenous gene expression. A, D–F: Whole-mount double antibody staining for endogenous protein expression and transgene-driven fluorescent protein expression. B, C: Fluorescent *in situ* hybridization for endogenous mRNA and antibody staining for transgene-driven fluorescent protein expression. The label above each panel indicates the endogenous protein or mRNA visualized and the transgene enhancer used. Filled arrows indicate cells coexpressing the transgene and protein or mRNA; open arrows indicate cells expressing only one or the other. Confocal images of the dorsal spinal cord were taken with a 20× objective and a 2× optical zoom; anterior is up. Scale bar, 50 μm. G: Quantification of coexpression between transgene and endogenous genes. The PKCα^{ct7a} line faithfully labeled all (100%) cells expressing PKCα protein, the *Fru.p2x3-2* reporter line labeled most (92%) *p2rx3a* mRNA-expressing neurons, and the *Fru.trkA* reporter line labeled the majority (60%) of *trkA* expressing neurons. Note that many neurons expressing *trkA* mRNA did not express the reporter, indicating variegation. PKCα protein was expressed in 46% of the total (*isl2b:GFP*-expressing) RB neuron population. PKCα endogenous expression almost perfectly colabeled neurons marked by the *Fru.p2x3-2* reporter line and vice versa. Expression of the PKCα protein only partially overlapped with *Fru.trkA* reporter line expression, as expected from analyzing transgene coexpression (Fig. 5). Because of variegation of the transgene (indicated by the asterisk), the number of neurons expressing PKCα protein only is an overestimate. n = total number of RB neurons.

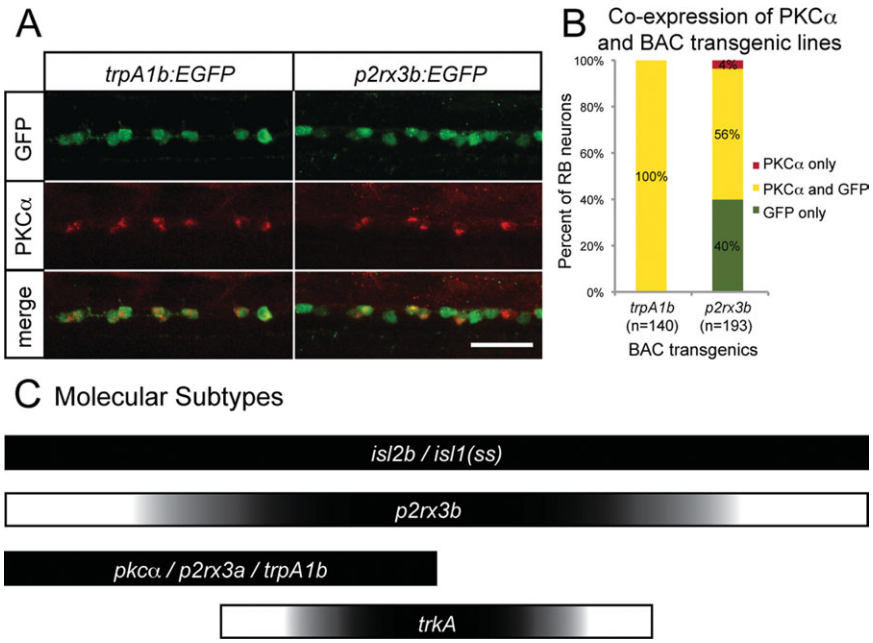

Figure 8 Transgenic lines label molecular subtypes of somatosensory neurons. A: Antibody staining for PKCα (red) and GFP (green) in 72 hpf *trpA1b:EGFP* and *p2rx3b:EGFP* BAC transgenic lines. Confocal images of the spinal cord were taken with a 20× objective and a 2× optical zoom; lateral images, anterior is left and dorsal is up. Scale bar, 50 μm. B: One hundred percent of *trpA1b:EGFP* RB neurons expressed PKCα. Approximately 56% of *p2rx3b:EGFP* RB neurons also expressed PKCα. *n* = number of RB neurons. C: Model for zebrafish larval RB neuron subtypes: *isl2b* and *isl1(ss)* highlight all RB somatosensory neurons. *p2rx3b:EGFP* expression labels most, if not all, RB neurons. PKCα, *p2rx3a*, and *trpA1b:EGFP* are coexpressed in a distinct population of neurons that make up ∼ 40% of all RB neurons. *trkA*-expressing neurons partially overlap with the PKCα/*p2rx3a* subtype.

VP16,4xLexAop:mCherry) larvae revealed that 92% of *p2rx3a*-expressing neurons also expressed the *Fru.p2x3-2* reporter, indicating that transgene expression faithfully recapitulated endogenous expression but was silenced in, at most, 10% of *p2rx3a*-expressing neurons. At 54 hpf, a larger proportion of neurons stained with the *p2rx3a* mRNA probe failed to express the reporter (20–35%, data not shown), perhaps reflecting cross-hybridization with the *p2rx3a* ortholog, *p2rx3b*, because increasing the hybridization temperature reduced the number of neurons that did not coexpress the transcript and the reporter.

To characterize *trkA* (also known as *ntrk1*) expression in the *Fru.trkA* reporter line, *Tg(Fru.trkA:Gal4-VP16,14xUAS:ChR2-YFP)*, we performed FISH for *trkA* mRNA and antibody staining for YFP at 32 hpf, when gene expression appeared to be highest. Sixty percent of neurons expressing *trkA* mRNA also expressed YFP, but few YFP-expressing neurons failed to express *trkA* [Fig. 7(C,G)]. This result confirms that the *Fru.trkA* reporter line is variegated (YFP was silenced in ∼40% of *trkA* neurons), but also that expression from the transgene faithfully reflects endogenous *trkA* expression.

To determine the relationship between the PKCα/*p2rx3a* subtype of RB neurons and expression in previously published *p2rx3b:EGFP* and *trpA1-b:EGFP* BAC reporter lines, we performed double antibody staining for GFP and endogenous PKCα in 72 hpf larvae from each of these BAC reporter lines. Approximately 56% of *p2rx3b:EGFP*-expressing RB neurons also expressed PKCα [Fig. 8(A,B)], indicating that PKCα/*p2rx3a*-expressing neurons are a subset of *p2rx3b:EGFP*-expressing neurons. This finding also suggests that *p2rx3b:EGFP* is expressed in most, if not all, RB neurons. In contrast, expression of the *trpA1b:EGFP* BAC reporter completely coincided with PKCα-expressing RB neurons. We have thus identified a subtype of RB neurons expressing three different transgenic reporter lines (PKCα/*p2rx3a*/*trpA1b)* and accurately reflecting the expression of genes involved in sensory signal transduction.

DISCUSSION

New Enhancers and Transgenic Reporters for Studying Zebrafish Somatosensory Neurons

To sense diverse touch stimuli, vertebrate somatosensation is carried out by several functionally and molecularly distinct sensory neuron subtypes. Although less well characterized, multiple somatosensory neuron subtypes exist even at early embryonic stages. Despite having morphologically similar cutaneous endings (O'Brien et al., 2012), subpopulations of RB neurons in larval zebrafish differentially express genes such as *pkcα*, *p2rx3a*, and specific sodium channels (Boué-Grabot et al., 2000; Norton et al., 2000; Slatter et al., 2005; Pineda et al., 2006; Appelbaum et al., 2007; Patten et al., 2007). To characterize the morphology, function, and connectivity of larval zebrafish somatosensory neuron subpopulations, we created several new reporter transgenes that express fluorescent proteins in these neurons using enhancers from neurotrophin receptors and ion channels. Some of the enhancers were cloned from the pufferfish genome, which we used because its more compact genome made it easier to identify regulatory elements. The fact that these enhancers drove expression in the expected neuronal populations indicates that they contain regulatory elements conserved at least among teleost fish. By dissecting these enhancer sequences and performing expression analysis, we identified several compact sequences (<200 bp) that are sufficient and/or required for somatosensory neuron expression, making them excellent starting points for identifying transcriptional regulatory motifs. Given their portability, strong expression, and temporal variability, these new enhancers and reporters will be useful tools for developmental and functional studies of zebrafish somatosensory neurons.

RB Neurons Possess Diverse Peripheral Axon Morphologies and Central Axon Termination Patterns, Even Within Molecularly Distinct Subtypes

Different axon morphologies may be optimized for the sensation of particular kinds of stimuli. In *Drosophila* and *Xenopus*, the complexity of cutaneous neurite branches defines functionally distinct somatosensory neuron subtypes (Hayes and Roberts, 1983; Grueber et al., 2003). Zebrafish trigeminal and RB neurons display a spectrum of arbor morphologies, prompting us to hypothesize that branching morphology is characteristic of RB subtypes as well. Analysis of branching morphology of RB neurons labeled by reporters driven by the *isl1(ss)*, *Fru.trkA*, *Fru.trkC*, and *Fru.p2x3-2* enhancers grouped axon arbors into five categories. However, most of these reporters were found in all five categories, potentially implying that branching morphology may be a stochastically determined property unrelated to sensory function.

Central axon termination patterns determine the potential neural circuits that a particular sensory neuron can activate. Touch usually elicits an escape response in larval zebrafish, but kinematically distinct patterns of escape can be distinguished (Saint-Amant and Drapeau, 1998; Liu and Fetcho, 1999; Drapeau et al., 2002; Burgess et al., 2009; Liu et al., 2012), implying that different circuits underlie them. The Mauthner cell is the central component of the classic escape response circuit (Liu and Fetcho, 1999; Korn and Faber, 2005; Kohashi and Oda, 2008). It was therefore surprising to find that the majority of RB neurons visualized with any of our transgenic reporters failed to contact the Mauthner cell dendrite, terminating instead within the spinal cord or caudal hindbrain. Touch can elicit escape responses in the absence of Mauthner cells (Liu and Fetcho, 1999; Burgess et al., 2009) or even of the entire hindbrain (Downes and Granato, 2006), implying that RB neurons must also connect to local spinal circuits. Mauthner-independent escape responses have a substantially slower latency than the classic escape response (Liu and Fetcho, 1999; Kohashi and Oda, 2008; Burgess et al., 2009), suggesting that non-Mauthner-contacting RB cells may elicit those slow responses. If that is the case, activating individual neurons within this class might elicit distinct behaviors. The new transgenic enhancers presented here provide valuable tools for addressing this hypothesis and for comprehensively analyzing the sensory and behavioral functions of subtypes of somatosensory neuron in larval zebrafish.

A Somatosensory Neuron Subtype Is Defined by PKCα and p2rx3a Expression

Analysis of the *PKCα*^{ct7a} gene trap line, the *Fru.p2x3-2* reporter line, and the *trpA1b:EGFP* BAC transgenic line revealed that they highlight the same population of RB neurons and faithfully reflect endogenous expression of PKCα and *p2rx3a*, thus defining a molecularly distinct somatosensory neuron subtype. To our knowledge, this is the first report of a somatosensory neuron subtype in zebrafish defined by more than one reporter or gene. In different experiments, the percentage of RB neurons

highlighted by these two reporters ranged from 30 to 50%, likely reflecting variability from animal to animal, but nonetheless consistent with previous reports that PKCα is expressed in ~40% of RB neurons (Slatter et al., 2005; Patten et al., 2007). PKCα is a kinase that functions in diverse signaling pathways, P2rx3a is an ATP-gated ion channel involved in nociception, and TrpA1b is a channel that is activated by pungent chemicals (Caron et al., 2008; Prober et al., 2008; Pan et al., 2012). This expression pattern suggests that these cells likely detect distinct nociceptive somatosensory stimuli and possess unique physiological properties. Because they likely detect distinct stimuli, the peripheral arbors of PKCα/*p2rx3a*/*trpA1b*-expressing neurons likely "tile" the skin independently of other RB neurons, so that animals can sense each modality throughout their body. This prediction remains to be tested, but our previous observation that each zebrafish trigeminal axon arbor repels approximately half of its neighboring arbors is consistent with this model (Sagasti et al., 2005).

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