MicroRNA Processing Pathway Regulates Olfactory Neuron Morphogenesis

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Summary

The microRNA (miRNA) processing pathway produces miRNAs as posttranscriptional regulators of gene expression. The nuclear RNase III Drosha catalyzes the first processing step together with the dsRNA binding protein DGR8/Pasha generating pre-miRNAs [1, 2]. The next cleavage by the cytoplasmic RNase III Dicer producing miRNA duplexes [3, 4]. Finally, Argonautes are recruited with miRNAs into an RNA-induced silencing complex for mRNA recognition (Figure 1A). Here, we identify two members of the miRNA pathway, Pasha and Dicer-1, in a forward genetic screen for mutations that disrupt wiring specificity of Drosophila olfactory projection neurons (PNs). The olfactory system is built as discrete map of highly stereotyped neuronal connections [5, 6]. Each PN targets dendrites to a specific glomerulus in the antennal lobe and projects axons stereotypically into higher brain centers [7–9]. In selected PN classes, pasha and Dicer-1 mutants cause specific PN dendrite mistargeting in the antennal lobe and altered axonal terminations in higher brain centers. Furthermore, Pasha and Dicer-1 act cell autonomously in postmitotic neurons to regulate dendrite and axon targeting during development. However, Argonaute-1 and Argonaute-2 are dispensable for PN morphogenesis. Our findings suggest a role for the miRNA processing pathway in establishing wiring specificity in the nervous system.

Results and Discussion

pasha and Dicer-1 Are Required for PN Dendrite Morphogenesis

To identify genes that are essential for dendrite targeting in Drosophila olfactory projection neurons (PNs), we performed a MARCM-based mosaic forward genetic screen by using novel piggyBac transposon insertions [10]. We uncovered the insertions LL03660 and LL06357, integrated in pasha and Dicer-1, respectively (Figure 1B). Both alleles are homozygous lethal, likely to be null, and referred to as pasha−/− and Dicer-1−/− mutants throughout this study. The pasha−/− allele is an insertion in the 5′ UTR, resulting in undetectable Pasha protein in homozygous mutant neurons (Figure S1 available online). The Dicer-1−/− allele is an insertion in the coding region resulting in a truncated 740 amino acid protein lacking the RNase III, PAZ, and dsRNA binding domains.

The MARCM technique [11] allows us to visualize and manipulate PNs in neuroblast and single-cell lines in an otherwise heterozygous animal. We use Gal4-GH146 [12] to label PNs from three neuroblast lineages, anterodorsal (ad), lateral (l), and ventral (v) PNs [7]. Wild-type (WT) adPNs, lPNs, and vPNs target stereotyped sets of glomeruli in neuroblast clones (Figure 1C1–3). pasha−/− PNs show two dendrite morphogenesis defects for all neuroblast clones. First, the dendritic density in most glomeruli is drastically reduced (compare outlined glomeruli in Figures 1C1 to 1D1 and 1C3 to 1D3). Second, dendritic branches split into incorrect glomerular classes (arrows in Figure 1D1–2). We observed very similar PN dendrite defects in Dicer-1−/− MARCM clones. Outlined glomeruli represent a reduction in dendrites and arrows point to incorrectly innervated glomeruli (Figure 1E1–3).

We confirmed that the transposon insertions in pasha and Dicer-1 are the cause for the mutant phenotype with two further experiments. First, precise excision of both transposons fully revert PN morphogenesis defects (data not shown). Second, expression of UAS-pasha-HA or UAS-Dicer-1 transgenes fully rescued pasha or Dicer-1 mutant PN phenotypes, respectively, in MARCM experiments (compare outlined glomeruli in Figures 1F and 1G to WT in Figure 1C1). Because Gal4-GH146 is expressed only in postmitotic neurons [13], these experiments also demonstrate that Pasha and Dicer-1 act in postmitotic neurons to regulate dendrite morphogenesis.

As expected, in all rescue experiments, Pasha-HA localizes to the nucleus (Figure 1F1–2 and insets of Figures 2D and 2E) and Dicer-1 is enriched in the cytoplasm of PNs (Figure 1G1–2 and inset of Figure 2F). Endogenous Pasha protein is found ubiquitously in all cell nuclei in the brain center at 18 hr after puparium formation (APF) (Figures S1A and S1B), when PN dendrites organize the proto-antennal lobe prior to olfactory receptor neuron (ORN) axon entry [14]. Moreover, Pasha is undetectable in pasha−/− adPNs and D1 single neurons (yellow outlines in Figures S1C1–1D1).

Dendrite Targeting in Specific PN Classes

To study dendrite targeting with a better resolution, we examined single-cell MARCM clones. WT DL1 single-cell clones (hereafter referred to as DL1 single neurons) always target a posterior, dorsolateral glomerulus and fill the glomerulus with dendritic branches (Figure 2A). In pasha−/− PNs, 17/25 DL1 single neurons show stereotyped mistargeting defects: dendrites innervate DL1 more sparsely and also mistarget to several additional glomeruli (VA7m, VC2, VA6, DL2d, and DL5), all of which are partially innervated (arrowheads in Figure 2B). 8/25 DL1 single neurons spill their dendrites medially to adjacent glomeruli, mostly D and DL5 (data not shown). Again, Dicer-1 single mutant neurons exhibit similar PN dendrite mistargeting although to a lower frequency. Similar stereotyped mistargeting pattern as in pasha mutants occur in 19/35 DL1 single neurons mutant for Dicer-1 (arrowheads in Figure 2C). 7/35 single neurons show mediolaterally spilled dendrites and 9/35 target normally (data not shown). The variation of DL1 phenotypes could be caused by perdurance of WT protein in single-cell mutant clones, which might affect Dicer-1 more than Pasha. The stereotyped DL1 targeting defect was not found in more than 1400 other piggyBac insertions scored (unpublished data), supporting the
specificity of the mutant phenotype for the miRNA processing pathway. MARCM expression of UAS-Pasha-HA in pasha
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2 or UAS-Dicer-1 in Dicer-1
2
2 DL1 single neurons fully rescued dendrite targeting (8/8 for pasha-HA rescue, Figure 2E; 4/4 for Dicer-1
rescue, Figure 2F), as is the case of neuroblast clones (Figures 1F and 1G). These experiments demonstrate that Pasha and Dicer-1 act cell autonomously in postmitotic neurons to regulate DL1 dendrite targeting.

To expand the studies of dendrite targeting to other specific PN classes, we used Gal4-Mz19 to label fewer neurons in neuroblast clones [14]. This Gal4 line labels w6 adPNs that innervate VA1d (asterisk) and DC3 (posterior to VA1d) in WT (Figure 2G). In 21/21 pasha-/- adPNs, VA1d/DC3 is sparsely innervated and dendrites are incorrectly targeted to variable glomeruli such as DA1, VA2, and VM7 (arrowheads in Figure 2H). 23/25 Dicer-1-/- PN mutants show similar medial mistargeting phenotypes albeit to a milder extent, innervating less distant glomeruli (arrowheads in Figure 2I). Similarly, the dendritic density is reduced and incorrect glomeruli are innervated, as in GH146 MARCM experiments (Figures 1D and 1E). Gal4-Mz19 is also expressed in w7 lPNs innervating the dorsolateral DA1 glomerulus in WT (Figure 2J). DA1 PN targeting is much less affected in pasha and Dicer-1 mutants. 4/5 pasha mutant and 7/9 Dicer-1 mutant lPNs target normally to DA1 with WT dendrite densities (Figures 2K and 2L), whereas 1/5 and 2/9 IPNs exhibit additional partial innervation of the adjacent DL3 glomerulus, respectively (data not shown). Thus, Pasha and Dicer-1 are not required equally in all PN classes, suggesting that potential miRNAs

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**Figure 1. pasha and Dicer-1 Are Required for Dendrite Morphogenesis of Olfactory Projection Neurons**

(A) Overview of miRNA-processing pathway. After transcription, pri-miRNA hairpin structures are cleaved by the RNAS III enzyme Drosha into a pri-miRNA of about ~70 nt length. Drosha requires the dsRNA binding protein Pasha for this processing step in the nucleus. The pri-miRNA is exported into the cytoplasm by Exportin-5 where it is cleaved into a ~21 nt long miRNA duplex by the RNAS III enzyme Dicer-1. The mature single-stranded miRNA is subsequently loaded into the Argonaute-containing RISC that binds to complementary miRNAs to regulate translation.

(B) Genomic organization of the pasha and Dicer-1 gene. Black bars represent coding and gray bars noncoding exons and the lines represent introns. Red triangles indicate the insertion sites of the piggyBac transposons LL03660 and LL06357. The insertion in Dicer-1 is in the first exon 2220 bp 3’ of the start codon. The insertion in Dicer-1 is in the first exon 2220 bp 3’ of the start codon.

(C) WT adPNs (C1), lPNs (C2), and vPNs (C3) target dendrites to stereotypical sets of glomeruli; VA1d and VA1lm adPNs are encircled (C1), as are DA1 and VA1lm vPNs (C3).

(D) pasha-/- adPNs (D1), lPNs (D2), and vPNs (D3) exhibit severe dendrite targeting defects, with a general reduction in dendritic mass (compare encircled glomeruli in [D1] and [D3] to WT in [C1] and [C3]) and spilling of dendrites into inappropriate areas (arrows in [D1–3]).

(E) Dicer-1-/- PN mutants show very similar targeting defects like pasha-/- PN mutants. (F and G) PN mutant phenotypes can be rescued completely by expressing either UAS-pasha-HA in pasha-/- mutant PNs (F) or UAS-Dicer-1 in Dicer-1-/- PNs (G). Pasha-HA localizes to the nucleus (F2), whereas Dicer-1 is enriched in the cytoplasm (G2) of PNs. Green is mCD8-GFP-labeled MARCM clones, red is the presynaptic marker nc82, and blue is anti-HA (F1) or anti-Dicer-1 (G1), respectively. Scale bar represents 20 µm. All images are z-projections of confocal stacks except in (F1), (F2), (G1), and (G2), which are single sections.
Pasha and Dicer-1 Regulate Axon-Terminal Arborization

In addition to dendrite mistargeting, we also observed axon defects in pasha and Dicer-1 mutants. WT DL1 axons project into the lateral horn (LH) via the mushroom body calyx (MBC) where they form several collateral branches. After entering the LH, DL1 axons always form one characteristic dorsal branch whereas the main branch terminates at the lateral edge of the LH (arrow and arrowhead, respectively, Figure 3A) [8, 9]. In pasha and Dicer-1 mutant DL1 single neurons, axons extend along the normal pathway, form collaterals in the MBC, and always reach the LH. However, more than half of the mutant DL1 axons do not reach the lateral edge but stop within the LH (arrowheads in Figures 3B and 3C). The dorsal branch in the LH is either absent (arrow in Figure 3C) or reduced in length (arrow in Figure 3B). Adding one copy of a UAS-pasha-HA transgene in pasha (data not shown) or UAS-Dicer-1 in Dicer-1 mutant DL1 single neurons rescued all axon phenotypes: the main branch fully extends to the lateral edge of the LH and the dorsal branch is indistinguishable from WT (arrowhead and arrow, respectively, in Figure 3D). Thus, Pasha and Dicer-1 cell autonomously regulate PN axon-terminal elaboration.

pasha Mutant Dendrite Defects Are Manifested during Development

To determine whether the PN dendrite targeting errors are a result of initial mistargeting or failure to maintain stable synaptic connections later, we performed developmental studies. At 18 hr APF, when ORN axons have not yet entered the proto-antennal lobe [14], WT adPN, IPN (Figure 4A1–2), and vPN (not shown) dendrites have already occupied a large area of the proto-antennal lobe (encircled and labeled with N-Cadherin antibodies in red). DL1 single neurons already target their dendrites in the area of the future DL1 glomerulus (arrowhead and arrow in Figure 3B). In pasha−/− PN axons, dendritic elaboration within the proto-antennal lobe is extremely reduced in all neuroblast or DL1 single-cell clones at 18 hr APF (outlined in Figure 4B1–3). At 50 hr APF, glomeruli become first visible [14]. In WT adPNs, IPNs, and DL1 single neurons, the same stereotyped innervation patterns as in adults are already evident even though the antennal lobe is smaller in its overall size (compare Figure 1C1–2 to 4C1–2 and Figure 2A1 to 4C3). Dendrites of pasha−/− PN axons are reduced in density (encircled in Figure 4D1) and spill into lineage-inappropriate glomeruli (arrowheads in Figure 4D1–2). Moreover, stereotyped mistargeting of DL1 single neurons is already evident in 4/4 pasha−/− PN axons at 50 hr APF (compare arrowheads in Figure 4D4 with Figure 2B).

These data, in combination with our observation that pasha mutant PN dendrite phenotypes do not vary in brains of 3- and 10-day-old adults (data not shown) indicate that Pasha regulates dendrite elaboration and correct targeting early during development.

Dicer-1, but Not Dicer-2, Is Required for PN Targeting

Dicer functions in small RNA maturation across species. Dicer mutants are defective for both transcript destruction and translational repression, suggesting that Dicer is required for the siRNA (small interfering RNA) and miRNA maturation pathway [4, 15]. However, the Drosophila genome contains two Dicer genes, Dicer-1 and Dicer-2, that share similar protein domains but are different in their functions. Dicer-1 and Dicer-2...
are both required for siRNA-dependent mRNA cleavage, with Dicer-2 acting in siRNA processing and Dicer-1 acting downstream of siRNA production. However, Dicer-1, but not Dicer-2, is essential for miRNA-induced silencing during translational repression [16].

To test whether the siRNA processing pathway is required for PN targeting, we made use of Dicer-2<sup>ΔL811fsX</sup> mutants that lack the two RNase III domains essential for dsRNA processing [16]. We found that Dicer-2<sup>ΔL811fsX</sup> mutant PNs exhibit normal dendrite and axon targeting (data not shown), suggesting that Dicer-2 is dispensable and the siRNA pathway is not required for PN targeting.

Next we asked whether Dicer-2 could compensate for Dicer-1’s function in PN targeting because their protein domain organization is highly similar. We expressed UAS-Dicer-2 in Dicer-1<sup>Δ</sup> PNs to test whether PN mistargeting phenotypes could be rescued as is the case for UAS-Dicer-1 expression. We saw no alteration in the Dicer-1<sup>Δ</sup>-dendrite mistargeting phenotypes in DL1 PNs (compare arrowheads marking mistargeted glomuerli in Figures S2A<sub>1</sub> and S2B<sub>1</sub>), adPNs, or pPNs (compare Figure S2A<sub>2</sub> to S2B<sub>2</sub> and Figure S2A<sub>3</sub> to S2B<sub>3</sub>). This observation suggests that Dicer-2 cannot replace Dicer-1’s function during PN targeting. We propose that Dicer-1-dependent PN targeting defects are caused by the absence of one or several miRNAs(s), because Dicer-1, but not Dicer-2, is essential for miRNA-directed translation repression and mRNA turnover.

**Normal PN Morphogenesis in AGO1 and AGO2 Mutants**

Many distinct mechanisms have been described for miRNA-mediated gene silencing (reviewed in [17]). However, for all these, the RNA-induced silencing complex (RISC) containing the Argonaute (AGO) proteins as core components is required (Figure 1A). AGO members can be divided into two groups, the ubiquitously expressed AGO and the reproductive cell-specific Piwi subfamily [18, 19]. The AGO subclass containing AGO1 and AGO2 in *Drosophila* is involved in small RNA loading into the RISC. Both miRNAs and siRNAs act as components of RISCs but use different silencing mechanisms. miRNAs typically contain several mismatches when paired with target mRNAs, causing mostly translational repression, whereas siRNAs are perfectly paired with target mRNAs leading to their degradation. AGO2 is described as a multiple-turnover RNA-directed RNA endonuclease acting in mRNA cleavage, whereas AGO1 functions in translational repression but also plays a role in efficient mRNA degradation [20]. However, mRNAs targeted by almost perfectly paired miRNAs can also be degraded via AGO2 [21, 22]. Thus, AGO1 is typically necessary for stable miRNA maturation and is essential for viability, whereas AGO2 is an essential component of the siRNA-directed RNA interference response [23, 24].

To determine which AGO member is involved in PN targeting, we examined MARCM clones of the strong loss-of-function allele AGO1<sup>ΔK08121</sup> and the AGO2<sup>ΔK414</sup> null allele [23, 24]. Surprisingly, we observed normal PN dendrite and axon targeting in AGO1<sup>ΔK08121</sup> and AGO2<sup>ΔK414</sup> adPNs (Figures 5A and 5C compare to WT in Figure 1C<sub>1</sub>, and data not shown), and DL1 single neurons as dendrites elaborate in the simple dorso-lateral DL1 glomerulus like in WT (arrowheads in Figures 5B and 5D, compare to Figure 2A). To test whether AGO1 and AGO2 could act in a redundant manner, we generated PN clones homozygous mutant for AGO1 in an AGO2 homozygous mutant background. 7/7 adPNs and 9/9 DL1 PNs exhibit normal targeting (Figure 5E and arrowhead in Figure 5F). In addition, axon-terminal arborization is normal in AGO1/AGO2 mutant DL1 cells (data not shown).

There are several explanations for this surprising result. First, the AGO<sup>ΔK08121</sup> allele may not be null. Second, perdurance of AGO1 protein from parental cells is capable of compensating for the loss of the AGO1 gene in homozygous mutant clones. AGO<sup>ΔK08121</sup> mutants have drastically reduced mRNA levels [23], AGO1 is absent in homozygous AGO<sup>ΔK08121</sup> embryo lysates, and AGO<sup>ΔK08121</sup> has been shown to disrupt stable miRNA maturation [24]. We also show that in AGO<sup>ΔK08121</sup> mutant wing disc clones miRNA function is disrupted as in *pasha<sup>Δ</sup>* and *Dicer-1<sup>Δ</sup>* clones by using a bantam sensor transgene (Figure S3; [25]). Because of these facts and given that WT AGO1 mRNA or protein would be heavily diluted at least in neuroblast clones, the above two explanations imply that a very small amount of AGO1 would be sufficient for PN dendrite targeting. Third, perhaps one or more members of the Piwi subfamily thought to be expressed [10], and given that the germline could compensate for the loss of AGO1/AGO2 in PNs. However, we observed normal PN morphogenesis in mutants for *piwi<sup>Δ</sup>l* [19] and *aubergine<sup>ΔL06590</sup>* [10], and both are Piwi subfamily members (data not shown). Lastly, PN dendrite targeting may utilize a novel miRNA-processing mechanism that is Dicer-1 dependent but AGO independent.

**Conclusion**

MicroRNA-mediated posttranslational regulation of gene expression has been documented in an increasing number of biological processes [26]. Many miRNAs are developmentally
regulated and show tissue-specific expression. In the nervous system, miRNAs have been shown to play roles during neurogenesis, specification of neuronal fate, neuronal morphogenesis, synaptogenesis, and neurodegeneration [27]. We have demonstrated a new function of the miRNA-processing pathway in regulating wiring specificity of the olfactory circuit.

Our results support the model that one or more miRNA(s) are essential for regulating expression of genes that in turn regulate PN dendrite targeting and axon-terminal elaboration in identified neurons during development. Candidate target genes could be transcription factors that regulate wiring specificity in postmitotic neurons, cell-surface receptors for dendrite targeting, or their regulators. Expression or protein levels of such genes are essential for PN dendrite targeting [28, 29]. However, each miRNA is predicted to target hundreds of mRNAs and several miRNAs can regulate one mRNA, adding much more complexity to their regulatory function [30]. Indeed, we tested 7 miRNAs with available null mutants (out of 152 miRNAs predicted in the Drosophila genome, see http://microrna.sanger.ac.uk/sequences); none of them exhibit PN targeting defects (Table S1). In flies, techniques that would allow the injection of individual or pools of mature miRNAs to rescue the neural phenotypes in pasha or Dicer-1 mutants, or mimic these phenotypes by injecting “target protectors” that interfere with miRNA-mRNA interactions as in zebrafish [31, 32], are currently not available. Therefore, it remains to be a future challenge to identify the miRNA(s), and ultimately their targets, for PN target selection. Looking for mutants with similar phenotypes as pasha and Dicer-1 in forward genetic screens or candidate gene approaches may help to identify specific miRNA and their targets.

Supplemental Data

Supplemental Data include Supplemental Experimental Procedures, three figures, and one table and can be found with this article online at http://www.current-biology.com/supplemental/S0960-9822(08)01275-X.
miRNA Processing in Dendrite Targeting

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