**Drosophila** Atonal controls photoreceptor R8-specific properties and modulates both Receptor Tyrosine Kinase and Hedgehog signalling

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**SUMMARY**

During *Drosophila* eye development, the proneural gene *atonal* specifies founding R8 photoreceptors of individual ommatidia, evenly spaced relative to one another in a pattern that prefigures ommatidial organisation in the mature compound eye. Beyond providing neural competence, however, it has remained unclear to what extent *atonal* controls specific R8 properties. We show here that reduced Atonal function gives rise to R8 photoreceptors that are functionally compromised: both recruitment and axon pathfinding defects are evident. Conversely, prolonged Atonal expression in R8 photoreceptors induces defects in inductive recruitment as a consequence of hyperactive EGFR signalling. Surprisingly, such prolonged expression also results in R8 pattern formation defects in a process associated with both Hedgehog and Receptor Tyrosine Kinase signalling. Our results strongly suggest that Atonal regulates signalling and other properties of R8 precursors.

Key words: *Drosophila melanogaster*, Proneural, *atonal*, Photoreceptor, *hedgehog*, Receptor Tyrosine Kinase (RTK)

**INTRODUCTION**

The *Drosophila melanogaster* adult compound eye is composed of approximately eight hundred facets, or ommatidia, arranged in a highly stereotypical hexagonal pattern (for reviews see Ready, 1989; Cagan, 1993). This pattern is established during the third larval instar in a process marked by the morphogenetic furrow (MF), a wave of apical cell constriction that traverses the unpatterned eye imaginal disc epithelium from posterior to anterior over a period of approximately 2 days (Heberlein and Moses, 1995; Treisman and Heberlein, 1998). As the MF moves, rows of evenly spaced cells are selected to become the ‘founding’ R8 photoreceptors, so-called because they initiate recruitment of the remaining cells of each ommatidium (Tomlinson and Ready, 1987; Freeman, 1996; Cagan, 1997). Since each R8 cell marks the position in which an ommatidium will form, pattern formation in the mature adult eye is determined during the larval stage by the position of R8 precursors relative to one another in the eye imaginal disc.

An essential component of R8 precursor selection is the basic-helix-loop-helix transcription factor encoded by the proneural gene *atonal* (*ato*) (Jarman et al., 1994). *ato* is required in the eye for the specification of R8 photoreceptors and elsewhere for the specification of chordotonal sense organs and a subset of olfactory organs. In common with other proneural genes, *ato* expression endows cells with neural competence. In the eye imaginal disc, *ato* is activated in an essentially homogeneous stripe along the anterior edge of the MF in response to *hedgehog* (*hh*) signalling from differentiating cells posterior to the MF (reviewed in Treisman and Heberlein, 1998). As the MF progresses, R8 spacing is decided by a complex and as yet partly understood process that restricts neural competence and *ato* expression to isolated R8 precursors (Jarman et al., 1994, 1995; Baker et al., 1996; Dokucu et al., 1996). Initially, the *ato* stripe resolves to evenly spaced clusters of approximately 12 cells, the ‘intermediate clusters’ (Jarman et al., 1995), and then to 2-3 cells, the ‘R8 equivalence groups’ (Dokucu et al., 1996). Ultimately, expression of *ato* in each R8 equivalence group resolves to a single cell, the R8 precursor, after which *ato* is downregulated (Fig. 1H). The restriction of neural competence to R8 precursors during eye development is reminiscent of the selection of sense organ precursors (SOPs) from neurally competent ‘proneural clusters’ in the peripheral nervous system (PNS) (Ghysen and Dambly-Chaudière, 1989; Ghysen et al., 1993). In both the eye and the PNS, the resolution of proneural expression depends on a common process, lateral inhibition. Thus, when mutated, genes such as *Notch* (*N*), *Delta* (*Dl*) and *scabrous* (*sca*) result in R8 hyperplasia (Cagan and Ready, 1989; Cubas et al., 1991; Parks and Muskavitch, 1993; Campos-Ortega, 1994; Baker et al., 1995; Baker and Zitron, 1995). *ato* resolution in the eye also has some distinct features, such as a requirement for *rough* (*ro*); in *ro* mutants most of the cells of the R8 equivalence group adopt an R8 fate (Dokucu et al., 1996).

Whilst many studies of *ato* and other proneural genes have concentrated on their neural competence function, less
attention has been paid to the possibility that these genes also determine specific neural properties of the different precursor subtypes they specify. Indeed, the progressive determination model of neural precursor selection proposed that selection (requiring proneural genes) is divorced from neural subtype specification (requiring subtype selector genes) (Ghysen and Dambly-Chaudière, 1989; Jan and Jan, 1993). This view may hold true for the proneural genes of the achaete-scute complex (AS-C) because they specify the precursors of a variety of cell types from equivalence groups in a range of neural and non-neural developmental contexts (e.g. Carmena et al., 1995). There are good reasons, however, to think that ato controls specific neural functions in addition to providing general neural competence (see also Jarman et al., 1993; Chien et al., 1996). First, ato is required for a few distinct subsets of sense organs and, in contrast to the AS-C, has no apparent function outside the nervous system. Second, ato seems to control specific functions of chordotonal sense organ precursors to make them distinct from the precursors of external sense organs specified by the AS-C (zur Lage et al., 1997; Jarman and Ahmed, 1998; zur Lage and Jarman, 1999). In the eye too, there is potential for similar ato functions: ato expression remains in R8 cells some 6-8 hours after their initial appearance, and so could control properties that make R8 photoreceptors distinct from the other photoreceptors (R1-R7) both physiologically and developmentally. For example, R8 acts as an organiser, triggering inductive recruitment of other cell types in the ommatidium through Receptor Tyrosine Kinase (RTK) signalling pathways (Tomlinson and Ready, 1987; Basler and Hafen, 1991; Freeman, 1996).

So far, mutant analysis has only revealed ato’s role in the selection of R8 cells, because these cells are completely absent in the described ato mutants (Fig. 1E,F); hence it has been impossible to analyse whether ato determines R8 properties after their selection. In such circumstances, gain-of-function studies can prove informative for uncovering additional gene functions, as shown by misexpression analysis of ato in chordotonal organ development (Jarman and Ahmed, 1998). In this report, we present evidence that ato indeed controls specific R8 properties. Firstly, we show in a hypomorphic ato mutant (ato^{2}) that reducing ato function specifically in selected R8 precursors renders them functionally compromised in photoreceptor recruitment and axon pathfinding. Secondly, we show by targeted misexpression that prolonged ato function within R8 cells increases inductive recruitment as a consequence of hyperactive EGFR signalling. Surprisingly, this misexpression also interferes with R8 precursor selection and pattern formation, apparently via Hh and RTK signalling. Interestingly, ato appears to modulate Hh signalling rather than control the overall level of Hh expression. We conclude that, in addition to endowing cells with neural competence, ato also controls some of the key functions of R8 precursors.

MATERIALS AND METHODS

Fly stocks

109-68Gal4 is an enhancer trap insertion on the second chromosome (Chien et al., 1996; Jarman and Ahmed, 1998). In all experiments, UAS-ato^{1} was used (Jarman and Ahmed, 1998). To generate the balanced 109-68Gal4, UAS-ato (ato^{109-68}/CyO) line, the 109-68Gal4 and UAS-ato elements were recombined onto the same chromosome. hh^{HC} is an amorphic allele of the hh gene, and hh^{pho} is an enhancer trap insertion at the hh locus (Ma et al., 1993). pts (tau^{2}), ro^{2}, sev^{2} (sev^{4}), phl^{P30} (phl^{1}), Egfr^{D} and Df^{1682} are all described in Lindsley and Zimm (1992). pts, ro, Egfr and Df alleles were all obtained from the Bloomington Stock Center. phl^{P30}, sev^{2} and Rax^{1-2} alleles were kindly provided by E. Hafen, and UAS-hh and hh^{120} by D. Strutt. ato^{1} is either a strong hypomorph or an amorphic allele of ato (Jarman et al., 1995). Enhancer trap lines marking photoreceptor subtype identity were XA12 for R7 (Modzik et al., 1990) and BBO2 for R8 (Hart et al., 1990) and were obtained from L. Zipursky. Crosses with 109-68Gal4 and ato^{109-68} were performed at 29°C to increase Gal4 activity (the severity of the phenotype is reduced at lower temperatures). All other crosses were performed at 25°C. Stocks were maintained on standard fly medium.

ato^{2} was isolated in an X-ray mutagenesis screen (E. H. G. Y. N. Jan, A. P. J., unpublished). Segregation analysis revealed an X-linked lethal mutation associated with the ato^{2} allele. Cytogenetic analysis of polytene chromosome squashes revealed the basis for this as a translocation of a large portion of the X chromosome into the ato region of the third chromosome (84F). This translocation is associated with complex genetics that makes manipulation difficult. It is homozygous lethal, and male sterile as a heterozygote due to compulsory simultaneous segregation of the deleted X chromosome.

Histology

Scanning electron microscopy (SEM) and sectioning of the adult retina were performed according to standard procedures (see the Carthew group website: http://info.pitt.edu/~carthew/manual/ Manual.html). All scanning electron micrographs were taken at 150× magnification. For immunohistochemistry, eye-antennal imaginal discs were dissected from wandering 3rd instar larvae and fixed in 3.7% formaldehyde (15 minutes). Incubations with primary and secondary antibodies were performed according to standard procedures. Light microscope images were taken on an Olympus Provis microscope. Confocal images were taken on an Leica TCS-NT microscope, and scanning electron micrographs were taken on a Cambridge Stereoscan 250. All images were adjusted and composed using Adobe Photoshop 3.0.

Antibodies

The following antibodies were used: mouse anti-β-galactosidase (1/1000; Promega), rabbit anti-β-galactosidase (1/10,000; Cappel), affinity-purified rabbit anti-Ato (1/2000), mouse anti-Bride of sevenless (Boss, 1/200; provided by S. L. Zipursky), rat anti-Ci (1/10; provided by R. Holmgren), and mouse mAb22C10 (1/200; Developmental Biology Hybridoma Bank, Iowa, USA). Secondary antibodies (used at a concentration of 1/1000) were obtained from Jackson Laboratories.

RESULTS

Evidence from a loss-of-function mutation that Ato regulates recruitment

The previously described ato mutant alleles show a complete failure to select R8 precursors (Jarman et al., 1994, 1995). Consequently, it has not been possible to determine whether ato has additional roles in determining the characteristics of R8 cells after their selection. We have therefore examined a weaker allele, ato^{2}. ato^{2}/ato^{1} flies have severely reduced eyes, which nevertheless contain ommatidia (approximately 200-300 in males, 5-15 in females), indicating that ato function and R8 selection are not entirely abolished (Fig. 1C,D). Sequencing revealed no mutations within the ato^{2} coding region. Instead,
molecular characterisation showed that an insertion had occurred between 7 and 8 kb upstream of the \( ato \) gene (unpublished data and Fig. 1A). Thus, \( ato^2 \) is a regulatory mutation in which an insertion has resulted in the separation of an eye-specific 5' enhancer element from the \( ato \) gene (Sun et al., 1998).

If \( ato \) has no function beyond R8 selection, one would expect that ommatidial assembly can proceed normally around the few R8 precursors that are formed in this mutant. This is not the case: ommatidia frequently lack the correct complement of photoreceptors, indicative of a recruitment defect. Detection of photoreceptor recruitment in imaginal discs confirmed this and showed that photoreceptor cluster sizes were variably reduced, containing from 1-8 photoreceptors (Fig. 1H). This suggests that recruitment may be blocked at any stage. Consistent with this, analysis of photoreceptor subtype markers showed that any or all recruited photoreceptors could be affected (data not shown) (although later cell types may be more frequently lost than earlier types).

Thus, it appears that the R8 precursors that form in \( ato^2 /ato^1 \) flies are functionally compromised. Significantly, the defects in recruitment correlate with the absence of \( ato \) expression from selected R8 precursors in \( ato^2 /ato^1 \) (Fig. 1J), as expected from the loss of an R8-specific enhancer. The loss of these cells suggests that although R8 selection can occur, \( ato \) expression is needed in these cells to regulate recruitment.

In addition to the recruitment defect, staining \( ato^2 /ato^1 \) eye discs with a cytoplasmic neural marker revealed that photoreceptor axon bundles frequently navigate incorrectly to the optic stalk (Fig. 1L). However, those axons that reach the optic stalk are able to continue to their target sites within the optic lobe (data not shown). Since photoreceptor axon pathfinding is thought to be guided by the R8 axon, the guidance defects evident in \( ato^2 /ato^1 \) are perhaps indicative of a lack of pathfinding properties in some R8 cells. Clearly, these findings are consistent with the idea that \( ato \) controls some of the neural properties of R8 photoreceptors.
of the disc in differentiating R8 cells.

The effect of aito misexpression is non-autonomous since the presence of supernumerary cells is not always correlated with ectopic Ato expression within them (data not shown). Since recruitment requires EGFR activity (Freeman, 1996), we tested genetically whether R8 precursors in aito/68 induce excessive photoreceptor recruitment via upregulated RTK signalling. This appears to be the case. Mutations reducing the efficiency of RTK signal transduction can suppress ectopic photoreceptor formation in aito/68. For example, the gene that encodes the Drosophila homologue of mammalian Ras-1 serine/threonine kinase (polehole (phl) Ambrosio et al., 1989) (Fig. 4B) and daughter of sevenless (dos) (Herbst et al., 1996; Raabe et al., 1996) (data not shown) gives strong suppression, whereas Ras mutants suppressed aito/68 somewhat less effectively (Fig. 4C). Reducing the dosage of EGFR itself also resulted in suppression of the recruitment defects in aito/68 (Fig. 4D). Thus, prolonged Ato induces recruitment defects via RTK signalling.

**ato/68-induced EGFR bypasses Sev signalling in R7 formation**

Among the recruitment defects in aito/68, analysis of sections (Fig. 3F) and enhancer trap elements expressed in specific subsets of developing photoreceptors revealed the pronounced occurrence of supernumerary R7 photoreceptors. R7 formation requires both EGFR and Sev signalling, but it is known that experimentally induced hyperactive EGFR can rescue R7 formation in the absence of sev (Freeman, 1996).
Therefore, we investigated whether excessive R7 formation in ato<sup>109-68</sup> was a consequence of either upregulated EGFR or Sev signalling. The former seems to be the case, since significant R7 recruitment still occurred in the absence of sev activity (which normally completely abolishes R7 formation). Thus in sevd<sup>2</sup>; ato<sup>109-68</sup> flies, 16±2% of ommatidia contained an R7-like cell as judged by morphology in eye sections (Fig. 4E). R7 formation was confirmed by R7-specific enhancer trap expression in eye discs (Fig. 4G). Furthermore, reducing EGFR gene dosage suppresses the ato<sup>109-68</sup>-dependent rescue of R7 recruitment in sev eyes (Fig. 4F; 6±1% of ommatidia contained an R7-like cell). Thus, EGFR signalling is hyperactive in ato<sup>109-68</sup> and, at the appropriate time in development, can bypass the requirement for sev during R7 recruitment. We have not ruled out the possibility that Sev signalling is also hyperactivated, although the suppression of recruitment defects by EGFR gene dosage reduction suggests it is not.

Prolonged ato expression non-autonomously induces R8 patterning defects

In the above experiments, we used the 109-68Gal4 driver to avoid directly altering ato patterning in the MF during R8 singling out, since this is known to disrupt R8 pattern formation (Dokucu et al., 1996; unpublished). Nevertheless, SEM, sections and disc stainings of ato<sup>109-68</sup> revealed...
additional defects consistent with a disruption in R8 pattern formation, despite the fact that there is no evidence for Gal4-driven expression during the process of R8 selection (Fig. 2B). Ommatidial spacing was abnormal, and there appeared to be fused ommatidia (Fig. 3C and data not shown). In ato109-68 discs, R8 cells are more dense, frequently juxtaposed (twinned), and unevenly spaced relative to one another, as shown by an R8-specific enhancer trap line (Fig. 5A,B) and the expression of endogenous ato itself (Fig. 2C). In addition, the normally regular refinement of ato expression is disrupted. These defects are reminiscent of R8 patterning mutations such as sca and ro, suggesting that mechanisms regulating endogenous ato expression during singling out are altered. This inference is supported by the observation that the ato109-68 patterning defect is sensitive to changes in the dosage of genes involved in ato regulation and R8 singling out, including ro (Fig. 5D) and DI (Fig. 5E), each as a result of the selection of an excess of R8 precursors (data not shown). As in mutants that disrupt R8 patterning, many of the later cell patterning defects appear to be a secondary consequence of the initial R8 patterning disruption.

Although R8 patterning depends on ato function, its disruption in ato109-68 initially appears counterintuitive, since R8 cells should already be correctly patterned prior to the onset of ectopic ato expression within them. Therefore these defects do not reflect a direct interference with R8 patterning processes. Instead, they must reflect an alteration of R8 behaviour that is non-autonomously transmitted to these earlier R8 patterning events. Interestingly, the phenotype is opposite to that expected from increasing ato function in R8 during selection itself. In this case, one might expect an increase in lateral inhibition, and hence a decrease in R8 formation and density. The inference is that we are detecting a hitherto uncharacterised function of ato in patterned R8 cells.

Defects in R8 patterning are associated with RTK and Hedgehog signalling

The effect of ato misexpression in selected R8 cells must be communicated to the process of selecting new rows of R8 cells within the MF. Interestingly, mutations of Raf strongly suppressed the effect of ato misexpression both at the level of adult ommatidial patterning (Fig. 4B) and R8 patterning in discs (data not shown), apparently indicating that Raf-dependent signalling mediates both recruitment and R8 patterning defects. However, reducing the gene dosage of EGFR did not appear to suppress defects in pattern formation or R8 precursor selection, even though defects in recruitment were clearly suppressed (Fig. 4D). Therefore, it is possible that defects in pattern formation depend on hyperactivation of an RTK other than EGFR.

In wild type, differentiating photoreceptors secrete Hh, which diffuses anteriorly across the MF to activate ato (Domínguez and Hafen, 1997; Strutt and Mlodzik, 1997; Domínguez, 1999) in cells previously inhibited by the transcription factor encoded by hairy (h) (Brown et al., 1995). This drives ato activation, and further R8 selection across the disc (Heberlein et al., 1993; Ma et al., 1993; Treisman and Heberlein, 1998). Therefore, defects evident in ato109-68 could be the result of a change in Hh signalling. Genetic interaction analysis strongly supports this possibility.

Mutations of hh (Fig. 6A,B) and its target gene cubitus interruptus (ci) (data not shown) are strong dominant suppressors of the ato109-68 rough eye and of R8 patterning defects (data not shown). Conversely, mutations of the inhibitory gene patched (ptc) were strong enhancers (Fig. 6C). Reducing the gene dose of h, which normally limits the Hh-induced anterior spread of the ato stripe (Brown et al., 1995), also enhanced the rough eye, albeit weakly (data not shown). Therefore, these genetic interactions are all consistent with an increase in extent and intensity of Hh signalling in ato109-68.

We analysed hh expression using an enhancer trap element (hhP30), which is reported to reflect faithfully endogenous hh activity (Ma et al., 1993). Surprisingly, in wild type little if any hhP30 expression was observed in R8, being instead largely restricted to photoreceptors R2 and R5 (Fig. 6D). Moreover, in ato109-68, hhP30 discs, β-galactosidase and Ato expression were not coincident, even in cases of R8 twinning in which an R2 or R5 precursor had been switched to an R8 fate (Fig. 6E). In addition, the level of hhP30 expression in ato109-68 was not, or at most only slightly, elevated in cells surrounding the R8s (Fig. 6E). Therefore, Ato is not a major activator of hh expression, either directly in R8 or indirectly in adjacent cells. On the contrary, ato may instead autonomously inhibit hh expression.

We next considered whether Hh activity is increased post-transcriptionally. The full-length form of Ci protein is stabilised by Hh signalling, and its abundance is therefore a reporter of Hh activity (Alexandre et al., 1996; Aza-Blanc et al., 1997). In wild type, this protein overlaps with Ato anterior to and within the MF (Fig. 6F) (Domínguez and Hafen, 1997; Domínguez, 1999). In ato109-68, Ci expression was increased in abundance in the eye disc compared with its expression in the adjacent antennal disc (Fig. 6G). This increase was frequently small and hard to detect, but became very obvious in eye discs in which the ato109-68 phenotype is enhanced by loss of one copy of ptc. In this case a clear increase in Ci level, and perhaps extent, was observed; such an increase was not apparent in ptc heterozygotes alone (data not shown).

hh upregulation does not itself result in patterning defects but enhances ato109-68

Is a general increase in Hh activity sufficient to explain the patterning defects? Additional experiments suggest not. When hh expression levels were elevated by driving hh itself in R8 cells (109-68Gal4; UAS-hh flies), Ci protein was clearly increased (Fig. 6H), but the eye of pharate adults appeared essentially wild type (data not shown), and ato refinement was unperturbed (Fig. 6H,J). Furthermore, when hh was ectopically expressed in all cells posterior of the MF using a strong Gal4 driver (GMRGal4UAS-hh) there was again no obvious effect on eye patterning of pharate adults (although the GMRGal4 construct itself produces a slight rough eye, data not shown). These experiments suggest that, under these conditions, the global level of Hh or Ci expression does not affect patterning. Significantly, however, when both ato and hh were ectopically expressed in R8 (109-68Gal4; UAS-ato; UAS-hh), the eye was extremely disorganised (data not shown) and ato expression was severely abnormal (Fig. 6L,K). Refinement of Ato to solitary R8 precursors rarely occurred, and the level of ato
expression within the MF fluctuated considerably. Thus, although increasing the level of hh expression alone does not induce defects in pattern formation, it strongly potentiates the effect of increased ato. These data together suggest that Ato modulates Hh signalling in a manner more subtle than regulating its overall intensity.

**DISCUSSION**

Using a combination of misexpression and loss-of-function genetic analyses, we have demonstrated that ato endows R8 cells with some key characteristics. The data indicate that in R8 ato modulates Hh signalling activity, initiates EGFR-dependent recruitment, and possibly regulates axon guidance. These findings support the concept that proneural bHLH transcription factors function not only to endow neural competence but also to control specific neural subtype properties. This has important implications not only for Drosophila neurogenesis, but also for the large number of vertebrate ato and AS-C homologues that have been identified. Indeed, recent studies indicate that at least some of the vertebrate ato homologues may also have subtype determining properties (e.g. Perez et al., 1999).

**ato controls EGFR-mediated recruitment by R8**

The hypothesis that ato determines characteristics within selected neural precursors was initially intimated from ato misexpression studies during chordotonal organ precursor selection. ato represses the homeobox gene cut, thereby diverting these precursors from an external sense organ fate and allowing them to adopt the alternative chordotonal organ fate (Jarman and Ahmed, 1998). Clearly, such aspects of ato’s subtype-determining properties must be contingent on the developmental context (chordotonal versus R8 precursor). One property, however, appears to be common to both developmental contexts: EGFR-mediated local recruitment. Both photoreceptors (Freeman, 1996) and chordotonal precursors (Okabe and Okano, 1997; zur Lage et al., 1997; zur Lage and Jarman, 1999) are clustered as a consequence of EGFR-dependent recruitment. In the case of chordotonal recruitment, we proposed that ato directly controls the level of EGFR signalling (zur Lage et al., 1997; zur Lage and Jarman, 1999). In the eye, although it is clear that R8 initiates recruitment, it was previously unclear whether this property is directly controlled by ato. Our experiments suggest that it is. Prolonging ato activity in R8 results in excessive recruitment as a result of hyperactive EGFR signalling. Conversely, reducing ato activity specifically in selected R8 precursors (ato2/ato1 flies) results in ommatidia that contain fewer photoreceptors than wild type. We postulate that these R8 precursors are unable to trigger recruitment efficiently. It is instructive to compare this with the Ellipse (Elp) mutation: superficially, the reduction in R8 selection observed in Elp mutants (Baker and Rubin, 1992; Alexander et al., 1999) resembles that of ato2. In contrast to ato2/ato1, however, the remaining ommatidia are of normal structure in Elp eyes, indicating that although fewer R8 precursors arise, they can function normally with respect to recruitment. Strikingly, whilst ato expression in selected R8 precursors is normal in Elp mutants (Jarman et al., 1995), it is not apparent in the R8 precursors in ato2/ato1, consistent with a role for Ato after R8 selection has occurred. In wild type, ato presumably triggers the initiation of signalling, since recruitment continues after ato is switched off. The appearance of ectopic R7 cells upon misexpression is, in this respect, an artefact of the delayed developmental timing of ato misexpression relative to wild type.

**Effects of ato in R8 on future R8 patterning**

Expression of ato in R8 photoreceptors induces defects in pattern formation at multiple stages of R8 singling out. Thus, ommatidial spacing is irregular as a result of aberrant spacing of the intermediate clusters, while twinning of R8 precursors is a consequence of a perturbation in fate refinement in the R8 equivalence group. Although ato is likely to be directly involved in these processes, the effect we have detected here is novel and unexpected, since we have misexpressed ato after these events have finished and so must primarily effect R8 behaviour subsequent to these processes. The effect of ato misexpression may therefore be communicated from the differentiating R8 cells to the MF. It is significant, therefore, that R8 patterning disruption in ato109-68 appears to be associated with both Hh- and Raf-dependent signalling. In both cases, increased signalling is associated with enhanced R8 formation. The Raf-dependent signalling is therefore distinct from the role of ato and EGFR signalling in intermediate cluster spacing (Domínguez et al., 1998; Spencer et al., 1998; Chen and Chien, 1999), which appears to be inhibitory via the activation of ro (Dokucu et al., 1996; Domínguez et al., 1998; Domínguez, 1999). Thus, we have detected a new ato- and Raf-dependent process that acts to promote subsequent R8 formation.

A weak gain-of-function ci mutation induces patterning defects similar to those induced by ato misexpression in R8 (Domínguez, 1999). This indicates that such defects in ato109-68 are feasibly explained by an effect on Hh signalling, yet it is unclear how perturbing Hh signalling (or Ci expression) disrupts pattern formation and R8 precursor selection. We found that simply increasing the amount of Hh (and consequently Ci) is not sufficient to disrupt R8 patterning. Moreover, it is clear that hh expression is not strongly regulated by ato either directly or indirectly. Of more importance may be local irregularities in Ci activation. An effect of this sort on pattern formation is consistent with the recent findings of Domínguez (1999). However, this study also proposed that Hh has two effects on ato expression: a long-range activation via ci and a short-range repression via ro in cells between the intermediate clusters (Dokucu et al., 1996; Domínguez, 1999). Our data are inconsistent with this model, since in ato109-68, R8 cells are more densely spaced rather than less so, even though one would predict that short-range R8 inhibition should be exacerbated (given that hh suppresses the defects of ato misexpression). A possible explanation is that ato in R8 specifically modulates long-range Hh signalling alone.

The RTK and Hh signalling may be unrelated, or one may be mediated by the other. Given that R8 is not the major site of hh expression, ato must modulate Hh function non-autonomously. It is possible that the Raf-dependent signalling inferred above could mediate the effect of ato in R8 on Hh signalling. For example, close juxtaposition of Ato- and Hh-
expressing cells (R8 and R2.5, respectively) suggests a speculative mechanism in which Ato might control components that promote Hh diffusion (Bellaiche et al., 1998). Alternatively, Ato may regulate an as yet unidentified diffusible factor that mediates a cell’s response to the Hh signal.

Fig. 6. Defects in pattern formation and R8 precursor selection in \textit{ato}^{109-68} are mediated by hyperactive Hh signalling. (A-C) Scanning electron microscopy of the adult compound eye. (A) \textit{ato}^{109-68/+}, (B) \textit{ato}^{109-68/++; hh^{32}/+}. Reducing the dosage of \textit{hh} clearly suppresses the \textit{ato}^{109-68} rough eye. (C) \textit{ato}^{109-68}/ptc^{5}. Reducing the dosage of \textit{ptc}, which limits precocious Hh signalling, enhances the \textit{ato}^{109-68} rough eye such that regions of hexagonal ommatidial packing are now rare. (D-K) Confocal microscopy of 3rd instar larval eye imaginal discs. (D,E) Immunohistochemical detection of Ato (green) and \textit{Boss} (red). Also, \textit{hh} expression is abolished in cells transformed by \textit{at} in \textit{ato}^{109-68}. In one example, in case \textit{ato}, but not \textit{hh}, is expressed in the R2 photoreceptor (yellow arrow), and in another, \textit{ato} is expressed in the mystery cell between R2 and R5 (blue arrow). (F-I) Immunohistochemical detection of Ato (green) and \textit{Ci} (red). In all cases, \textit{Ci} abundance in the eye disc was normalised by comparison with its abundance in the adjacent antennal disc. (F) Wild type. (G) \textit{ato}^{109-68/+}. The abundance of \textit{Ci} is marginally higher in \textit{ato}^{109-68} relative to wild type. (H) \textit{109-68Gal4/+; UAS-hh/+} (i.e. without UAS-\textit{ato}). Although the abundance of \textit{Ci} is clearly increased, there is little or no evidence of defects in R8 patterning or selection. (I) \textit{ato}^{109-68/+}; UAS-hh/+ When both UAS-\textit{hh} and UAS-\textit{ato} are present, pattern formation and R8 precursor selection are severely abnormal. (J,K) Detection of Ato (green) and Boss (red). (J) \textit{109-68Gal4/+; UAS-hh/+}. (K) \textit{ato}^{109-68/+}; UAS-hh/+ . There is a dramatic failure to resolve Ato to spaced R8 cells.

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