Sensory neurons of the Atonal lineage pioneer the formation of glomeruli within the adult Drosophila olfactory lobe

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SUMMARY

The first centers for processing of odor information by animals lie in the olfactory lobe. Sensory neurons from the periphery synapse with interneurons in anatomically recognizable units, termed glomeruli, seen in both insects and vertebrates. The mechanisms that underlie the formation of functional maps of the odor-world in the glomeruli within the olfactory lobe remains unclear. We address the basis of sensory targeting in the fruitfly Drosophila and show that one class of sensory neurons, those of the Atonal lineage, plays a crucial role in glomerular patterning. Atonal-dependent neurons pioneer the segregation of other classes of sensory neurons into distinct glomeruli. Furthermore, correct sensory innervation is necessary for the arborization of projection neurons into glomeruli and for the elaboration of processes of central glial cells into the lobe.

Key words: Atonal, Antennal lobe, Olfactory glomeruli, Projection neurons, Glia, Drosophila

INTRODUCTION

Diverse odors are detected by sensory neurons and represented in the olfactory lobes in anatomically identifiable regions called glomeruli. Functional imaging experiments in insects (Rodrigues, 1988; Hansson et al., 1992) and, more recently, in vertebrates have established that odor information is encoded as a spatial map of glomerular neural activity (Rubin and Katz, 1999; Uchida et al., 2000). Each sensory neuron in the fruitfly Drosophila typically projects to a single identifiable glomerulus and synapses on to interneurons of central origin (Stocker, 1994). Projection neurons from glomeruli target to higher centers in the mushroom body and the lateral horn. In addition, a number of local interneurons connect glomeruli either within the same lobe or between contralateral lobes. Each glomerulus is ensheathed by glial cell projections (Jhaveri et al., 2000a). What are the relationships between peripheral neurons and their central targets during development, resulting in the organized development of olfactory glomeruli?

Large families of candidate chemosensory receptors have been identified in several different animals by experimental approaches or by the use of novel computer algorithms (Buck, 1996; Vosshall et al., 1999; Clyne et al., 1999; Gao and Chess, 1999; Stortkuhl and Kettler, 2001). Results from in situ hybridization experiments in Drosophila, have shown that, with a few minor exceptions, each olfactory neuron expresses a single receptor gene (Vosshall et al., 1999; Clyne et al., 1999). Neurons expressing a given receptor type appear to converge largely onto a predominant glomerulus in each olfactory lobe (Vosshall et al., 2000; Gao et al., 2000). A similar topographic map has been described in the olfactory bulb of rodents (Ressler et al., 1994; Vassar et al., 1994; Royet et al., 1998). Receptor substitution experiments as well as mutation of receptor genes in mice has provided compelling evidence for the role of odorant receptors in the formation of the topographic map (Mombaerts et al., 1996; Wang et al., 1998).

A model in which the selective expression of receptor genes within olfactory neurons is itself instrumental in guiding axons to defined targets is an elegant explanation for generation of the odor map. However this mechanism is unlikely to be widely applicable across species. In the zebrafish, a population of transient, clonally distinct set of pioneer neurons, which do not express odorant receptors, prefigure the olfactory pathway (Whitlock and Westerfield, 1998). Similarly, in Drosophila, expression of odorant receptor genes occurs late in pupal development, well after patterning of the lobe is completed (Vosshall et al., 1999; Clyne et al., 1999; Jhaveri et al., 2000a). This suggests that novel and rather complex developmental mechanisms must operate in these systems to create odor-specific neural maps within the adult brain.

A large body of evidence that has accumulated from studies of the moth olfactory pathway has shown that the sensory neurons are instructive in determining glomerular patterns (Schneiderman et al., 1986; Oland and Tolbert, 1998; Rossler et al., 1999a; Rossler et al., 1999b). Transplantation of the male antennal disc into female pupae leads to formation of a male-specific macroglomerulus, which is important for sensing of sexual pheromones. This and other investigations suggest that the sensory neurons are essential for organizing the specificity
of glomerular formation during development. However, it seems unlikely that lobe interneurons are passive partners during glomerular formation; Malun et al. (Malun et al., 1994) ablated sensory neurons and demonstrated that a few ‘glomerular-like’ structures could still be formed. The olfactory lobe is therefore a unique system for the study of how interactions between sensory neurons, interneurons and glial cells can define functionally distinct neural structures.

We investigate the role of sense organ specificity in the choice of central targets. There are three morphologically distinct sense organs on the surface of the antenna: sensilla coeloconica, basiconica and trichoidea (Venkatesh and Singh, 1984). We have previously shown that the helix-loop-helix transcription factor, Atonal (Ato) is necessary and sufficient for formation of the coeloconic sensilla (Gupta and Rodrigues, 1997; Jhaveri et al., 2000b). A related proneural protein, Amos, is required for the specification of the other two types of sensilla (Goulding et al., 2000). Expression of amos is regulated by the runt domain transcription factor Lozenge (Lz), which appears to regulate the choice between basiconic and trichoid sensilla in a dose-dependent manner (Gupta et al., 1998). We show that neurons of the Ato lineage are the first to enter the nascent adult olfactory lobe and are necessary for the correct targeting of other sensory neurons into the lobe. In mutants where Ato neurons fail to form, the afferents of other sense organs at first remain stalled at the periphery and although they ultimately enter the lobe, they fail to target correctly. As a consequence, glomerular formation is disrupted. The projection of central glial cells within the lobe is affected and postsynaptic interneurons enter the lobe normally but fail to terminate in glomeruli. This suggests that an intimate interaction between sensory neurons, projection neurons and glia during development orchestrates glomerular patterning, with sensory neurons of one class pioneering the organization of all sensory inputs crucial for this process.

MATERIALS AND METHODS

Fly stocks

B. Shymala (Shymala and Chopra, 1999) kindly provided the SG18.1-Gal4 enhancer trap line, MZ317-Gal4 was a gift from Kei Ito and GH146 from Reinhard Stocker. The ato strains - ato1/TM3, ato2/FM6, Df(3R) p13/TM3 and UAS-Ato were obtained from Andrew Jarman (Jarman et al., 1995). ato1 is either a strong hypomorph or an amorphic allele; the strain carries a closely linked lethal, making it inviable as a homozygote. The phenotype can be examined by placing it in trans with a deficiency (Df(3R) p13) for the region. The ato2 allele is a hypomorph caused by an insertion into the region upstream of the gene with no change in the coding region. The strain carries a translocation of part of the X chromosome onto the autosome requiring that both X and third chromosomes must segregate together (White and Jarman, 2000). lz1 was obtained from Reinhard Stocker; UAS dominant negative Cdc42 (UAS-DNc42) and UAS-Rac12 were obtained from the Jan laboratory; and UAS-GFP (1010T2) was obtained from Barry Dickson. Balancer and marker stocks were kindly provided by the Fly Stocks center at Bloomington, Indiana (Lindsley and Zimm, 1992).

To visualize sensory neurons and glial cells in strong ato hypomorphs, stable stocks of SG18.1 UAS-GFP; ato1/CyO-Tb and MZ317 UAS-GFP; ato1/CyO-Tb and MZ317 UAS-GFP; ato1/CyO-Tb were generated and crossed to Df(3R) p13/TM3-actin-GFP. ato1/Df(3R) p13 pupae were selected based on the absence of balancers. Weaker ato heteroallelic combination was obtained by individually crossing SG18.1 UAS GFP; ato1/CyO-Tb and MZ317 UAS GFP; ato1/CyO-Tb to ato1/FM6. The reduced ommatidial phenotype was used to select for ato1/ato2 animals.

All flies were reared at 25°C on a standard cornmeal media containing yeast. For staining, white puparia [0 hours after puparium formation (APF)] were collected and allowed to develop on moist filter paper at 25°C unless otherwise mentioned. The white pupal stage lasts for 1 hour hence the error in staging is ±30 minutes. Wild-type Canton-Special (CS) pupae emerge within 100 hours after white puparium stage at 25°C. Developmental times in all other genotypes were normalized with respect to that of the CS strain.

Immunohistochemistry

Dissection and antibody staining of the pupal and adult brain wholemounts were carried out as described elsewhere (Jhaveri et al., 2000a). The primary antibodies used were 22C10 (1:50; from S. Benzer’s laboratory), anti-Fas II, ID4 (1:5; from Corey Goodman), anti-Dachshund (1:25, Developmental Studies Hybridoma Bank at University of Iowa) and rabbit anti-Repo (1:250, from Gerd Technau). Secondary antibodies used were Alexa 568-coupled goat anti-mouse and anti-rabbit IgG (Molecular Probes), and Cy5-conjugated goat anti-mouse and anti-rabbit IgG (Amersham). The labeled samples were mounted in anti-fading agent, Vectashield (Vector Laboratories), imaged on BioRad Radiance 2000 at 1 μm intervals, and data were processed using Confocal Assistant and Adobe Photoshop 5.0.

Cuticle preparation

Adult antennae were placed in a drop of Faure’s mountant (34% v/v chloral hydrate, 13% glycerol, 20 mg/ml gum Arabic, 0.3% cocaine chlorhydrate) and allowed to clear overnight on a heating block at 70°C. Olfactory sense organs on the third antennal segment were counted by projecting images on the video monitor. A minimum of 10 samples was analyzed in each case to compute the mean and standard deviation.

In situ hybridization

Digoxigenin-labeled riboprobes were generated for Or22b, which was cloned in pGEM-T Easyvector (a kind gift from John Carlson) using standard methods. RNA in situ hybridization was performed as described (Clyne et al., 1999) on 10 μm frozen antennal sections. Digoxigenin-RNA probe was visualized using alkaline phosphatase-conjugated anti-digoxigenin antibody (Boehringer Mannheim).

RESULTS

Each sensory neuron from the third antennal segment projects to a single glomerulus and, in the majority of cases, sends a collateral branch to the corresponding glomerulus on the contralateral side (Stocker et al., 1990). The SG18.1-Gal4 enhancer-trap strain was used to drive a green fluorescent protein (GFP) reporter specifically in sensory neurons, allowing visualization of their presence during glomerular development (Brand and Perrimon, 1993). In the antenna, SG18.1-Gal4 is expressed in all olfactory neurons, although more strongly in the coeloconic and trichoid sense organs (Shymala and Chopra, 1999). In adult lobe, well-patterned identifiable glomeruli and the inter-antennal commissure can be clearly discerned (Fig. 1A,G,J). Synaptic maturation within the glomeruli can be visualized by staining with antibodies against the immunoglobulin superfamily member, Fasciclin II (Fas II) (Schuster et al., 1996; Jhaveri et al., 2000a). The glomerular pattern resembles that seen in the adult by 60 hours after formation of the white puparium (APF) (Fig. 1B).
about this time, odorant receptor expression in the sensory neurons is first detected, making it unlikely that the receptors play any role in the targeting of sensory neurons to the olfactory lobe (Clyne et al., 1999).

In order to test whether sense organ type affects lobe patterning, we examined the projection patterns of the sensory neurons in mutants that lack specific sense organs. Mutations in \textit{ato} affect specifically the coeloconic sense organs (Gupta and Rodrigues, 1997) while the \textit{lz} locus affect both basiconica and trichoidea (Stocker et al., 1993).

Absence of cells of the Ato-lineage affects segregation of neural inputs from all olfactory sense organs

Flies of genotype \textit{ato}^{1/Df(3R)p^{13}} lack all coeloconic sensilla on the antenna (Gupta and Rodrigues, 1997). These sense organs are each innervated by two or three sensory neurons (Shanbhag et al., 1999); as there are about 75 coeloconica, approximately 200 of the total of 1200 sensory axons would be absent in animals that lack \textit{ato}^{+} function. We traced the projection patterns of the residual (~1000) neurons projecting from sensilla basiconica and trichoidea on the antenna by examining GFP expression in animals of the genotype SG18.1 UAS-GFP/+; \textit{ato}^{1/Df(3R)p^{13}} lobes of the first sensory afferents to enter the brain are those of the Ato lineage (Jhaveri et al., 2000a). These neurons enter the brain at 20 hours APF and remain on the periphery of the lobe in close association with glial cells until about 30 hours APF. Soon after, these neurons, together with the projections from other sensilla, which have by then arrived within the brain, invade the lobe, and glomerular formation begins at about 36 hours APF. In \textit{ato} mutants, the residual sensory afferents stall at the periphery of the lobe up until the mid-pupal stage (compare Fig. 1F with 1C) with only very few stray fibers actually projecting into the lobe (small arrows in Fig. 1F). Later in development, afferents do enter the lobe but remain disorganized with no obvious glomerular structures (Fig. 1D,E). The antennal commissure fails to form, suggesting that even though the sensory neurons of the basiconic and trichoid sensilla can enter the lobe in the
absence of the Ato lineage, they do not send collateral branches to the contralateral lobe (Fig. 1D). These phenotypes could, in principle, arise from the lack of Ato function in the brain. We examined the presence of lobe associated interneurons by staining with anti-Dachshund (blue in Fig. 1G,H), and glia with anti-Repo (red in Fig. 1G,I) and find that these are normal in ato− mutants.

Our data demonstrate that the lack of coeloconic sense organs affects patterning of all sensory neurons within the antennal lobe, including those arising from other sensilla. The fact that the Ato-dependent sensilla are the first to appear within the antennal disc is consistent with this lineage playing a pioneering role during lobe development.

Absence of sense organs specified by Lz affect only those glomeruli which receive inputs from these neurons

Null alleles at the \(lz\) locus lead to an absence of all basiconic sensilla and a large subset of trichoid sensilla (Gupta et al., 1998). In \(lz^2\) animals only ~300 of the 1200 olfactory neurons form (Stocker, 1994; Shanbhag et al., 1999). Serial confocal sectioning of \(lz^2\; SG18.1\) UAS-GFP/+ adult lobes allowed the identification of most glomeruli seen in wild-type controls (Fig. 1J,K). The prominent ‘V’ glomerulus was absent, as described before (Stocker and Gendre, 1988; Laissue et al., 1998). In antennal segment, although cells of the Johnston’s organ in sensilla and a large subset of trichoid sensilla (Gupta et al., 1999), and some central glomeruli formed in the mutants. Staining of 60 hour pupal lobes with (white dots in Fig. 1J), although present, were poorly formed in the mutants. Staining of 60 hour pupal lobes with anti-FasII antibodies revealed several well-defined glomeruli (Fig. 1L).

Late expression of Ato in neurons does not rescue antennal lobe patterning defects

Hassan et al. (Hassan et al., 2000) have shown that Ato plays a regulatory role in the arborization of neurons during pupal life, perhaps by an interaction with Notch. We tested whether the patterning defects observed in the olfactory lobe of ato− mutants could be explained by a later role in arborization, rather than being a consequence of the lack of proneural function leading to the absence of coeloconic sensilla. We expressed Ato in sensory neurons that still formed in ato\(^+/Df(3R)p^{13}\) animals using the SG18.1 UAS-GFP/UAS-Ato; ato\(^+/Df(3R)p^{13}\) genotype. The aglomerular phenotype could not be rescued by Ato ectopic expression and the lobes closely resembled those of strong ato hypomorphs (compare Fig. 2A,B with Fig. 1D). In the wild type, ectopic expression of Ato in all olfactory neurons using Neuralised-Gal4 or SG18.1-Gal4 did not affect glomerular formation (data not shown).

Gupta and Rodrigues (Gupta and Rodrigues, 1997) showed that Ato expression begins in the antennal disc of the third larval instar and decays by about 12 hours APF. This is consistent with a role for ato as a proneural gene. We stained pupal antenna between 18 hours and 36 hours APF, a period when sense organs undergo differentiation (Fig. 2C). No Ato immunoreactivity was detected at these times in the third antennal segment, although cells of the Johnston’s organ in second segment showed expression (Fig. 2D). No Ato immunoreactivity was seen in the developing antennal lobe at any pupal age (not shown).

In order to test whether differentiation of sensory neurons was affected by lack of ato− function, we examined the expression of candidate odorant receptor genes in the antenna. In situ hybridization to sections of adult Drosophila antenna using a digoxigenin-labeled Or22b probe showed normal expression in a subset of large basiconica in wild type as well
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neurons (Clyne et al., 1999). This demonstrates that the onset of receptor gene expression is not affected in situations where central connectivity is compromised. These results together provide strong evidence that the cells of the Ato lineage, probably the neurons themselves, play a pioneering role in glomerular patterning.

The ato lineage is the source of peripheral glial cells, required for the fasciculation of all sensory neurons, but not for lobe development
Jhaveri et al. (Jhaveri et al., 2000a) had shown that sensory progenitors selected by ato + function give rise not only to neurons and support cells of the sensilla coeloconica but also to the majority of the antennal glia. Repo-positive glial cells migrate along the developing neurons and their processes ensheathe the sensory axons into three distinct fascicles (designated 1, 2, 3 in Fig. 3A). In ato/Df(3R)p13 animals, peripheral patterning is affected; only one major fascicle is observed as the axons exit the antenna (Fig. 3B). There is also a striking reduction in the number of peripheral glia; we could count only 35±1 glia compared with 100±6 in the wild type. The majority of the antennal glia therefore arise from the gliogenic Ato lineage, while a small population are Ato independent and could have a central origin (Jhaveri et al., 2000a).

As ato mutants affect both glial as well as sensory neurons, the primary cause of the fasciculation defect in the antenna is unclear. In order to test the possible causal role of glia in sensory fasciculation, we specifically perturbed development of these cells using the Gal4/UAS system. Mis-expression of a dominant negative form of Cdc42 (DN-Cdc42) using the glial-specific MZ317-Gal4 line, would be expected to block cell growth because of disruption of cytoskeletal polarity (Jhaveri et al., 2000a; Dickson, 2001). We observed a reduction in glial cell number, presumably because of cell death, and remaining cells were aggregated with no apparent processes (Fig. 3C and inset). Sensory neurons showed a range of defects in fasciculation, some of which closely resembled that of ato mutants (Fig. 3C).

These observations demonstrate a role for glia in segregation of sensory axons in the adult peripheral nervous system. One

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possibility is that these glia, which ensheath the peripheral axons, also play a role in the sorting of afferents into glomeruli. The presence of glial sorting zones that direct migration of olfactory neurons to target glomeruli has been shown in the moth *Manduca sexta* (Rossler et al., 1999a). We stained the lobes of MZ317-Gal4 UAS-GFP/UAS-DN-CDC42 with an antibody against FasII (Fig. 3D-F). Glomeruli developed normally in spite of a reduction of peripheral glial numbers and defective organization of the sensory neurons at the periphery. MZ317-Gal4 also expresses in the glial cells around the lobe (green in Fig. 3D,F). Somewhat surprisingly, we did not observe any obvious defects in the location of the lobe-associated glia or their extensions into the lobe (arrow in Fig. 3F).

Hence, while peripheral glia instruct patterning of the olfactory neurons at the periphery into distinct fascicles, they play no role in the organization of the antennal lobe. We conclude that the focus of the defect in lobe patterning seen in *ato* hypomorphs lies within the neurons arising from the coeloconic sense organs.

Expression of constitutively active Rac in neurons does not affect peripheral fasciculation but phenocopies the *ato* defect in the lobe

Rho GTPases form an important link between signaling cues and the actin cytoskeleton; thus, ectopic expression of constitutively active or dominant negative forms in neurons could lead to defects in growth cone motility (Dickson, 2000). We mis-expressed activated Rac in olfactory neurons using SG18.1-Gal4 and observed no defect in the peripheral organization of the olfactory neurons (Fig. 3G). Interestingly, the lobes of SG18.1-Gal4 UAS-GFP/UAS-RacV12 appeared remarkably similar to those of *ato* loss-of-function animals (compare Fig. 3H with Fig. 1D). The neurons were disorganized within the olfactory lobe and the inter-antennal commissure was not formed. The phenotype that we observe could result from an abrogation of proper signaling between neurons during lobe formation or be due to a failure of growth cone extension of Ato-dependent neurons into the lobe.

The patterning defect in the antennal lobe can be ‘rescued’ by the presence of a small subset of Ato neurons

Antenna from *ato*/*Df(3R)p13* animals completely lacked coeloconic sensilla (compare Fig. 4B with 4A). Weaker hypomorphic allelic combinations - *ato*/ato2 - allowed formation of a smaller number of coeloconic sensilla (arrowheads in Fig. 4C). The antennal lobes of these animals showed normal glomeruli and the presence of the inter-antennal commissure (compare Fig. 4D,E with Fig. 1A,G). The presence of about 20 coeloconic sensilla in these mutants would contribute to about 50 sensory neurons. This means that the presence of even a small fraction of Ato-dependent neurons is sufficient to provide instruction to the rest of the afferents for correct targeting.

Sensory inputs act to organize central glia and interneurons within the lobe

Our data so far have shown that the presence of Ato-dependent neurons is crucial for organization of the rest of the afferents within the lobe. Does the defect in sensory neurons also affect the targeting of central glial cells and interneurons? Most of the glial cell bodies lie at the periphery of the lobe (arrowheads in Fig. 5A) with only a few within the lobe itself (not shown). In lobes from *ato*/Df(3R)p13, we had observed a normal distribution of Repo-positive glial cells associated with the lobe (Fig. 1F). The glial processes visualized in MZ317 UAS-GFP/+; *ato*/Df(3R)p13, however, showed aberrant hyper-branching within the lobe (Fig. 5B). We had previously shown that in the wild type, glial process invade the lobe at approximately the same time as those from the sensory afferents (Jhaveri et al., 2000a). The phenotype in *ato* mutants suggests that the correct extension of glial processes to ensheath individual glomeruli is regulated by interaction with the sensory neurons. The elaboration of glial processes is normal in the weaker hypomorphic combination *ato*/ato2 (Fig. 5C).

Do the sensory neurons influence arborization of the lobe interneurons into specific glomeruli? The interneurons are of two broad classes: (1) the projection neurons that arborize within
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single glomeruli and send axons into higher brain centers including the mushroom body and the lateral horn; and (2) the local interneurons that connect the glomeruli within the same lobe and also connect corresponding glomeruli in both lobes (Stocker, 1994). The GH146-Gal4 line coupled with GFP allows the visualization of about 90 projection neurons that lie in three clusters anterodorsal, lateral and ventral to the antennal lobe (Stocker et al., 1997; Jefferies et al., 2001).

We used the GH146 line to study the effect of sensory innervation on projection neuron targeting. In late pupae, these neurons target to well defined glomeruli (asterisk in Fig. 5D,E). Patterning of these interneurons is temporally correlated with the arrival of sensory neurons into the lobe; hence, at the mid-pupal stage (~45 hours APF), several glomeruli become recognizable (Fig. 5G, asterisk). In ato1/Df(3R)13 pupae, projection neurons enter the lobe but fail to target to proto-glomerular sites (Fig. 5F,H). These neurons invade the lobe well before sensory neurons have differentiated (Fig. 5I). At this stage, however, there is no evidence of glomerular patterning and dendrites of the projection neurons have not yet occurred. Scale bars: in A, 20 μm for A-C; in D, 20 μm in D-I.

**DISCUSSION**

Our results from the genetic manipulation of sensory neurons on the antenna can be interpreted in the context of the events that take place during normal development. The adult olfactory lobe in Drosophila is built upon a pre-existing larval structure by addition of interneurons that arise by proliferation of identified neuroblasts during larval life (Tissot et al., 1997; Stocker et al., 1997; Jefferies et al., 2001). The glomerular innervation of these interneurons is pre-specified by lineage and birth order, and they enter the pupal lobe well before sensory neurons are chosen from cells on the antennal disc (Ray and Rodrigues, 1995; Reddy et al., 1997) (Fig. 6A). At this stage, however, there is no evidence of glomerular patterning and dendritic arborization of projection neurons occurs after targeting of sensory afferents is initiated (Fig. 6A). This leads us to propose a functional role as pioneers to neurons projecting from the Ato-derived sense organs.
The adult olfactory lobe is built upon a pre-existing larval template using instructive cues from sensory inputs

*Drosophila* larvae have rather well developed olfactory behavior; although the level of discrimination is not as sophisticated as that in the adult (Monte et al., 1989; Ayyub et al., 1990). Exposure to chemical stimuli at the larval stage can influence olfactory behavior in the adult (Thorpe, 1939; Tully et al., 1994). It is tempting to speculate that the larval olfactory lobe provides a pre-pattern upon which adult structures are remodeled. There are about 21 larval olfactory neurons that project from the dorsal organ to glomerular-like terminals within the lobe (Heimbeck et al., 1999). Before histolysis, the larval antennal nerve serves to guide axons of the adult olfactory neurons, which arise in the antennal disc, to the brain (Tissot et al., 1997).

Evidence in a variety of insect species has shown that in the adult, sensory inputs are instructive for glomerular development. (Tolbert and Sirianni, 1990; Oland and Tolbert, 1996). We have shown that the instructive role of afferents can be divided into two steps. First, one in which one class of sensory neurons plays a crucial role and, next, a possible general role for sensory inputs. It is remarkable that the Ato-lineage neurons are essential for this process, it could be argued that they are not sufficient to pattern glomeruli. In *lz* nulls, about 300 olfactory sensory neurons are seen, about half of which arise from *lz*-independent trichoida (Gupta et al., 1998). Could these remnants sensilla trichoidea be involved in a pioneer role similar to those of the Ato-lineage? Our results cannot exclude such a role for these neurons. However, there are several reasons, taken together, that suggest Ato-lineage neurons are essential for the process of glomerular patterning. First, neurons of the Ato-lineage arrive at the olfactory lobe before other sensory afferents. Second, mis-expression of Ato in all lineages using Neuralised-Gal4 converts most neurons to coeloconica (Jhaveri et al., 2000a; Jhaveri et al., 2000b). In this situation, glomerular patterning is normal. Finally, mutants in the proneural gene *amos* lack all basiconic and trichoid sensilla and, here too, glomerular formation takes place (Goulding et al., 2000) (Anindya Sen and Andrew Jarman, personal communication). Thus, with the current availability of reagents and methods, it appears that Ato-lineage neurons are sufficient for glomerular development.

**Neurons of the Ato lineage are both necessary and sufficient for glomerular patterning**

While glomerular patterning fails in *ato* mutants, indicating that the Ato-lineage neurons are essential for this process, it could be argued that they are not sufficient to pattern glomeruli. In *lz* nulls, about 300 olfactory sensory neurons are seen, about half of which arise from *lz*-independent trichoida (Gupta et al., 1998). Could these remnant sensilla trichoidea be involved in a pioneer role similar to those of the Ato-lineage? Our results cannot exclude such a role for these neurons. However, there are several reasons, taken together, that suggest Ato-lineage neurons are essential for the process of glomerular patterning. First, neurons of the Ato-lineage arrive at the olfactory lobe before other sensory afferents. Second, mis-expression of Ato in all lineages using Neuralised-Gal4 converts most neurons to coeloconica (Jhaveri et al., 2000a; Jhaveri et al., 2000b). In this situation, glomerular patterning is normal. Finally, mutants in the proneural gene *amos* lack all basiconic and trichoid sensilla and, here too, glomerular formation takes place (Goulding et al., 2000) (Anindya Sen and Andrew Jarman, personal communication). Thus, with the current availability of reagents and methods, it appears that Ato-lineage neurons are sufficient for glomerular development.

**What is the role played by Ato-dependent neurons in setting up the functional map in the antennal lobe?**

Functional mapping experiments have shown that odor quality is represented as a spatial map of activity among the olfactory glomeruli (Rodrigues, 1988; Hansson et al., 1992). Vosshall et al. (Vosshall et al., 2000) and Gao and Chess (Gao et al., 2000) have shown that neurons expressing a given olfactory receptor terminate within the same glomeruli in the *Drosophila* antennal lobe. A similar topographic mapping been described in vertebrates; evidence from these systems suggests that odorant receptors themselves play a role in guiding neurons to their targets (Mombaerts et al., 1996; Wang et al., 1998). The...
mechanisms that underlie such guidance phenomena are unclear and, in addition, raise the question of how receptor gene regulation is specifically regulated. In Drosophila, the onset of receptor expression relative to the time of lobe development makes it very unlikely that odorant receptors play a role in the primary events in receptor axon targeting. Moreover, we find that ubiquitous expression of some of the olfactory receptors in all the sensory neurons throughout development does not affect glomerular patterning (D. J. and V. R., unpublished).

Neurons of the Ato lineage have the capacity to target the lobe and project to most glomeruli. They may then serve as somewhat general guideposts for other sensory neurons that then distribute themselves to specific glomeruli in response to short-range signals. How does such a developmental model incorporate the invariant distribution of odorant receptors among sense organs on the antennal surface and their stereotypic projection to glomeruli? One possibility is that the Ato-dependent pioneers project specifically to targets of glomerular formation in the lobe primordium. These neurons attract sensory neurons from other lineages that are fated to express the same receptor gene. This, however, begs the question of how groups of pioneers acquire distinct properties to enable their specificity of projection and ability to select discrete populations of neurons. A somewhat similar phenomenon occurs during development of the zebrafish olfactory system where antigenically and clonally distinct pioneer neurons guide other neurons to specific targets within the lobe (Whitlock and Westerfield, 1998). These pioneers are not completely analogous to the Ato neurons, as they are transient and do not eventually express odorant receptors.

The targeting of pioneer neurons and subsequent patterning of a functional map must involve combinatorial cues that could exist as a pre-pattern in the developing lobe. Identification of molecules that set up such a developmental field is now possible because of identification of a large number of putative cell surface molecules from Drosophila genome analysis (Schmucker et al., 2000). We suggest that in response to these cues, Ato-dependent neurons not only project correctly but also play an active role in guiding other sensory neurons to defined glomeruli.

Jeffries et al. (Jeffries et al., 2001) have postulated that neurons from the input and output fields of the olfactory lobe are independently specified and that choice of glomerular targets of the projection neurons is predetermined early in development. In such a scenario, projection neurons should target and arborize correctly in the lobe, even in situations where sensory input is lacking. We found that this was not the case; in ato- mutants, the interneurons though present within the lobe failed to terminate within defined glomerular sites. We propose that despite the possible existence of autonomous developmental programs within the interneurons, cues from sensory inputs are still essential to trigger proper patterning.

The complex interaction between Ato-lineage pioneers, sensory neurons, projection neurons and glia underlies a novel mechanism that operates during development of a functional neural map within the olfactory lobe. While we do not yet know what the operative mechanism is, we now have a genetic handle that will allow the design of experiments that seek to identify it.

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REFERENCES


