Timing of Wingless signalling distinguishes maxillary and antennal identities in Drosophila melanogaster

Gaelle Lebreton, Christian Faucher, David L. Cribbs* and Corinne Benassayag

INTRODUCTION

Most of the external cuticle of the adult fruit fly Drosophila melanogaster derives from epidermal structures called imaginal discs (Morata, 2001). The eye-antennal (E-A) imaginal disc gives rise to the major head sensory organs (eyes, ocelli, antennae and maxillary palp) (Haynie and Bryant, 1986), making it a model for the development of multiple organs from a composite rudiment. From the second larval instar onwards, the complementary expression domains of the transcription factors eyeless (ey)/twin of eyeless (toy) and cut (ct) define fields that ultimately yield the eye and antenna, respectively (Dominguez and Casares, 2005; Kenyon et al., 2003). Axial organisation of the antenna employs a canonical genetic cascade typical of ventral appendages, analogous to the one described for legs (Brook et al., 1996). This cascade starts with the expression of the homeobox selector gene engrailed in the posterior compartment, where it specifies posterior cell fate and activates transcription of the hedgehog (hh) gene. Hedgehog protein secreted by posterior cells diffuses across the AP boundary to nearby anterior cells, where it activates the transcription of target genes, including decapentaplegic (dpp/TGF-β) anterodorsally and wingless (wg/Wnt) anteroventrally (Diaz-Benjumea et al., 1994; Lecuit and Cohen, 1997). Mutual antagonism between these two morphogen growth factors is necessary to activate expression of the homeodomain transcription factor Distal-less (Dll) in the centre of the disc, thereby setting the proximodistal (PD) axis (Diaz-Benjumea et al., 1994; Lecuit and Cohen, 1997). Activation of Dll in the antennal disc leads to the co-expression of Dll and the TALE homeodomain protein Homothorax (hth; the Drosophila Meis1 homolog), whereas they do not overlap in the leg disc (Dong et al., 2001). Two lines of argument indicate that Dll and hth jointly specify antennal fate. First, haploinsufficient alleles of Dll or mitotic clones of hth- cells can transform antennae into legs (Casares and Mann, 1998; Dong et al., 2000; Dong et al., 2001). Second, ectopic co-expression of Dll and hth can cause transformations to antenna (Dong et al., 2000; Dong et al., 2002). Dll and hth are thus required, respectively, for the specification of the distal versus the proximal domains of ventral discs but also for the specification of antennal fate (Abu-Shaar and Mann, 1998; Dong et al., 2000; Dong et al., 2002; Wu and Cohen, 1999). They regulate multiple target genes during antennal development that function in specifying antennal structures and/or repressing leg development (Casares and Mann, 1998; Dong et al., 2000; Dong et al., 2002). One of these targets is spineless (ss), which encodes a b-HLH-PAS protein homologous to the mammalian Aryl Hydrocarbon Receptor (Duncan et al., 1998). ss is considered to be an antennal selector gene as the antennae of ss- adults are transformed to distal legs while the mis-expression of Ss induces ectopic antennal structures in adult legs (Dong et al., 2002; Duncan et al., 1998; Struhl, 1982). Ss controls distal antennal differentiation at least in part via the activation of its target genes distal antenna (dan) and distal antenna related (dan-r) that encode nuclear ‘pipsqueak’ motif proteins (Emerald et al., 2003). Ectopic expression of dan or dan-r causes a partial transformation of distal leg towards antenna, whereas loss of both functions has the opposite effect (Emerald et al., 2003; Suzanne et al., 2003). They are thus considered to be effector genes of antennal identity.

Though the antennal imaginal disc has often been treated as a single cellular field giving rise to the adult antenna, it has long been known that the second olfactory organ of the adult head – the maxillary palp – also originates from the antennal disc (Haynie and Bryant, 1986). A maxillary (Mx) primordium that gives rise to the adult maxillary palp emerges from the antennal disc as a localised outgrowth in early pupae (Jurgens and Hartenstein, 1993). However, very little has been described concerning the developmental origins of the Mx palp, nor of the genetic program leading to its final form. Two of the antennal determinant genes, Ss and Dll, are known to be required for Mx development, as loss of
their functions leads to adults with reduced or deleted Mx structures, respectively (Cohen and Jurgens, 1989; Duncan et al., 1998). Consistent with these mutant phenotypes, both Dil and ss are expressed at the pupal stage in the Mx primordium of the antennal disc (Duncan et al., 1998; Panganiban, 2000). Contrary to the antenna, recent work places Dil downstream of ss in the maxillary field (Emmons et al., 2007). Additionally, the homeotic genes proboscipedia (pb; HoxA2/B2) and Deformed (Dfd; Hox A4-D4) are both expressed in the Mx primordium (Benassayag et al., 2003; Diederich et al., 1991) and required there, as adult Mx palps are deleted by mitotic Dfd clones, and reduced in pb homozygotes (Merrill et al., 1987; Pultz et al., 1988). As ectopic pb expression transforms distal antennae into Mx palps, pb is considered to be a Mx selector gene (Cribbs et al., 1995). The reciprocal transformation of Mx into antennae can be observed when ss or wg are mis-expressed in Mx cells (Duncan et al., 1998; Johnston and Schubiger, 1996). Thus, the antennal and Mx organs appear to be homologous structures that emerge from the same imaginal disc, share key selector genes involved in their specification and both contribute to adult olfactory function.

In this paper, we address the issue of regional specification of the Mx field within the antennal disc. We find that the Mx field is defined by Deformed expression from the second larval instar onwards. The program for Mx regionalisation that emerges here is a temporally deferred version of the antennal program, owing to the delayed expression of the ventral signal Wg in the prepupal Mx field. We show that precocious wg expression in this tissue is sufficient to transform Mx to antenna, indicating that the delayed Wg expression in the Mx primordium is crucial in distinguishing antennal and Mx identity. Finally, our analysis reveals that Wg acts through ss in the maxillary field, but wg can also influence organ identity independently of the ss selector function.

### MATERIALS AND METHODS

The 180° rotation of the eye-antennal disc during development results in an inversion of dorsal and ventral cells. To avoid confusion, we employ the convention that dorsal cells are those that express dpp.

**Drosophila strains and transgenic lines**

The strain used as wild type in this study was w. Reporter genes used were dpp-lacZ BS3.0 (Blackman et al., 1991) and ptc-lacZ (Zhang and Kalderon, 2000). The ss null allele ss3 (ss) is described by Duncan et al. (Duncan et al., 1998). For targeted mis-expression, ptc-GAL4 driver line (Hinz et al., 1994) was used with responder constructs UAS-ss (Duncan et al., 1998) or UAS-wg5 M7-2.1 (Wildier and Perrimon, 1995). The fly strains employed for clonal analysis were: (1) w; FRT82B, (2) hs-FLP, w; FRT82B Ub-GFP, M(3)Rps3/TM6B, Ht, Th, (3) y w hs-FLP; FRT82B pygoglo130/TM6B, Ht Th, (4) y hs-FLP; FRT42D Ub-GFP/Cyo, and (5) y w; FRT42D Dll–/SM5–/TM6B, Ht Th. Stocks specifically constructed for this work were: (1) ptc-GAL4; ss–/TM6B, Ht Th, (2) UAS-wg5, ss–/TM6B, Ht Th, (3) hs-FLP; ptc-GAL4; FRT82B pygoglo130/TM6B, Ht Th, and (4) UAS-ss; FRT82B Ub-GFP Rps3/TM6B, Ht Th.

**Conditions for temporal wg activation**

After crossing ptc-GAL4 and UAS-wg5 flies, egg layers were collected for 24 hours, and then adults were removed to fresh medium. Development is slowed for this genotype (Johnston and Schubiger, 1996). Developing animals were maintained at 25°C for 1 day (~L1), 2 days (~L2), 3 days (~early L3), 4 days (~mid L3), 5 days (~late L3) or 6 days (~early pupa), then shifted to 18°C to activate wg. Dan staining was performed on imaginal discs from late L3 larvae or from pupae, depending on the timing of wg activation. For molecular analysis the woglo and wg65, ss larvae (ptc-GAL4+/−; FRT82B ss+/UAS-wg5, ss) were shifted to 18°C during L3 stage, after 4 or 5 days of development.

**Clonal analysis**

Clones were generated using the FLP/FRT system (Xu and Rubin, 1993).

For lineage analysis, Minute-enhanced mitotic clones were induced in hs-FLP; FRT82B; FRT82B Ub-GFP M(3)Rps3 animals by a single 30-minute heat shock at 38°C (condition where there is one clone per antennal disc) after about 1 (L1), 2 (L2), or 3 (L3) days of development.

In the other experiments, clones were generated by a single 1-hour heat shock at 37°C during the first or second larval instar, then dissected and stained in late third instar or in pupal discs: in hs-Flp; FRT82B pygoglo130/FRT82B Ub-GFP, M(3)Rps3 animals for pygo mutant clones; in hs-Flp; ptc-GAL4/UAS-ss; FRT82B pygoglo130/FRT82B Ub-GFP, M(3)Rps3 (ss58, pygo) for pygo mutant clones overexpressing ss; or in hs-Flp; FRT42D Dll–/SM5–/FRT42D Ub-GFP for Dll mutant clones.

**Immunocytochemistry and antibodies**

Larvae or white pupae were prepared for immunofluorescence essentially as described by Agnes et al. (Agnes et al., 1999). All incubations were performed without agitation to avoid damaging the pupal tissues. Primary antibodies used were: mouse anti-Cut 2B10 (1/200), concentrated anti-Inv 4D9 (1/20) and anti-Wg 4D4 (1/200) from the Developmental Studies Hybridoma Bank (DSHB); mouse anti-Dll, 1/500 (I. Duncan); rabbit polyclonal anti-Dfd, 1/250 (T. Kaufman); rabbit anti-Hth, 1/250 (N. Azpiazu); rat polyclonal α-Dan, 1/300 (S. Cohen); guinea pig anti-Ss, 1/1000 (L. Jan and Y. N. Jan); and rabbit anti-βGal, 1/5000 (Cappel, Promega). Mounted discs were viewed using a Zeiss LSM410 or a Leica TCS SP2 confocal microscope.

**Adult cuticle analysis**

Flies of interest were stored in ethanol until dissection. Detailed examinations of dissected heads mounted in Hoyer’s medium were performed by light microscopy on a Zeiss Axiophot.

### RESULTS

**Distinct antennal and maxillary territories are established early in larval development**

The antennal disc gives rise to two distinct olfactory organs: the antenna and the maxillary palp which is derived from a small bud-like primordium in the pre-pupal disc (Jurgens and Hartenstein, 1993). Two Hox genes required for Mx differentiation, proboscipedia (pb) and Deformed (Dfd) (Merrill et al., 1987; Pultz et al., 1988), are expressed in the Mx territory: Pb is initiated in the pre-pupal Mx primordium and Dfd is present in L3 (Benassayag et al., 2003; Diederich et al., 1991). We therefore examined expression of the Dfd protein as a potential molecular marker to follow maxillary development within the antennal disc. Dfd already accumulates in maxillary cells in early L2 larvae, the period at which segregation of the eye and antennal territories occurs (Kenyon et al., 2003), in a pattern complementary to the antennal field marker Cut (Fig. 1A).

This pattern of exclusion between Cut and Dfd then persists both in the disc proper and in the peripodial membrane through L3 (Fig. 1B), in early pupae (Fig. 1C), and into metamorphosis, where Dfd remains in the Mx palps of a pupal head after fusion of the eye-antennal and labial discs (Fig. 1D, arrows). We conclude that Dfd marks a Mx field that is present in the antennal disc from the L2 larval stage onwards into pupal development.

To test whether the exclusive patterns of Dfd and Cut markers reflect separate cell populations, we examined growth-enhanced wild-type mitotic clones that touch the Dfd/Cut limit in the posterior antennal disc; see Fig. 1B,C. In the conditions used, most antennal discs contained one or no clones. Most clones induced from L2 onwards were restricted to the maxillary (12/33; Fig. 1D), in early pupae (Fig. 1C), and into metamorphosis, where Dfd remains in the Mx palps of a pupal head after fusion of the eye-antennal and labial discs (Fig. 1D, arrows). We conclude that Dfd marks a Mx field that is present in the antennal disc from the L2 larval stage onwards into pupal development.
clones encompassed both posterior antennal and maxillary cells, while a significantly larger proportion of clones induced in L1 larvae did (18/59 clones). This difference indicates that the expression domains detected with Dfd and Cut markers in early L2 reflect the establishment of a clonal restriction between Mx and antennal fields.

The Mx organ employs a temporally delayed version of the antennal program

Very little is known about how the Mx organ is patterned. We therefore examined the expression of known participants of the genetic cascade common to ventral appendages, and directly compared expression of these markers between the adjacent Mx and antennal territories of the same imaginal disc (Fig. 2).

Initial anteroposterior specification involves expression of engrailed/invected (en/inv) that determines posterior cell identity and activates transcription of the hedgehog (hh) morphogen there. In L2 larvae, the single group of cells expressing En/Inv/Hh proteins in the antennal disc is restricted to the antennal territory, as it does not overlap with Dfd-expressing cells (Fig. 2A,B; data not shown). Unexpectedly, the Hh transcriptional target patched (ptc) is activated on both sides of these posterior antennal cells, bordering them in adjacent anterior antennal cells but also in the maxillary field (Fig. 2F,G; as seen by a ptc-lacZ transgene that recapitulates normal ptc expression). The same result was obtained with antisera directed against Ptc protein or the activator form of the Hh target protein patched (Fig. 2L). ptc expression in late L2 (Fig. 2G) is not accompanied by dpp or wg (Fig. 2L). dpp-lacZ expression in the maxillary territory appears in early L3 larvae (Fig. 2M). By contrast, Wg is absent throughout L3 development (Fig. 2M,N), and only appears nearly 2 days later at the L3/pupal transition, in anterior maxillary cells, adjacent to (and exclusive of) those expressing Dpp (Fig. 2O). Mitotic hh clones confirmed that this maxillary wg expression is hh dependent (not shown). In prepupae, Dll appears in a group of Mx cells centred on the Dpp-Wg junction that largely overlaps Hth there (inset, Fig. 2T). Dac is not detected in the Mx primordium (not shown). These data, summarised at the bottom of Fig. 2, indicate that the maxillary region deploys a program similar to the antennal program but delayed by the late appearance of Wg.

Timing of wg signalling defines maxillary versus antennal identity

Temporally regulated Wg thus might play a key role in distinguishing the genetic programs leading to maxillary and antennal fates. One described consequence of mis-expressing Wg is the transdetermination of maxillary palps to antennae (Johnston and Schubiger, 1996). We re-examined this effect of Wg on Mx/Ant identity, paying particular attention to the temporal activity of Wg. A conditionally active WgG4 protein that is secreted at 18°C but not at 25°C (Gonzalez et al., 1991; Wilder and Perrimon, 1995), was driven by ptc-Gal4 for varied times and durations at 18°C (Fig. 3; see also Materials and methods). Mx-to-Ant transformations were scored by two criteria: (1) expression of antennal markers, especially Dan, in the Mx territory of the E-A disc (Fig. 3A), and (2) appearance of identifiable adult antennal tissue, notably aristae, in place of Mx palps (Fig. 3B, arrow).

ptc-Gal4>UAS-wgG4 animals that develop at 25°C eclose as normally patterned adults (not shown). Animals raised at 18°C from embryogenesis onwards all died before L2. By contrast, shifting from 25 to 18°C during larval development yielded a Mx-to-Ant transformation whose frequency was strongly influenced by timing (see table in Fig. 3). When the passage to 18°C was carried out in L1 larvae, we observed significant numbers of transformed larvae/pupae and adults (28% of Dan-expressing discs, 53% of adults with Mx-to-Ant transformation). The penetration of the transformation was markedly enhanced when the permissive temperature was installed later, in L2 (63% and 85%), early L3 larvae (73% and 90%) or mid-L3 (83% and 89%), then maintained until adult eclosion. Thus, the most efficient conditions leading to Mx-to-Ant transformation were those where Wg was over-expressed concomitantly with Dpp in Mx cells (see Fig. 3).
Temperature shifts to 18°C of pre-pupa produced almost no transformation (6% and 7%). This result shows that overexpression of the Wg morphogen in pre-pupa is not sufficient to direct Mx-to-Ant transformation, and indicates that precocious Wg activation is a crucial initiator of Mx-to-Ant transformation. We infer that the rare individuals obtained with Mx-to-Ant transformation under this condition have probably been subjected to Wg overexpression during the late L3 stage, in light of the 24-hour egg-lay periods employed (see Materials and methods). Finally, when transgenic Wg was expressed solely during the L3 larval stage, no transformed individuals were obtained (0/26), suggesting that continuous expression of Wg and/or a precise spatial pattern of ectopic expression are required for efficient transformation. These results were confirmed using the flip-out technique to generate new sources of Wg that do not depend on the ptc promoter. Wg-expressing clones (act>y+>wg) induced by hsFlp in second instar larvae were sufficient to trigger aristal formation on adult Mx palps and ectopic Dan expression in the L3 larval Mx field (not shown). Taken together, these results indicate that temporal control of wg activity in pre-pupa versus larvae is crucial to distinguishing the Mx-specific developmental program from its antennal counterpart.

**wg signalling controls maxillary ss expression**

Mis-expressing Wg is sufficient to provoke a Mx-to-Ant transformation. However, the same transformation is induced on mis-expressing Spineless (Ss) antennal selector protein under ptc-Gal4 control (Duncan et al., 1998). We therefore compared the temporal and spatial maxillary expression of Wg and Ss. In the wild-type Mx territory, both Wg and Ss are absent in L3 (Fig. 2M,N; not shown), then appear simultaneously there at the L3-prepupal transition (Fig. 4A), followed in prepupa by Dll activation in a subset of ss-expressing cells (Fig. 4B). Mis-expressed Wg induces a precocious Mx expression of Ss and Dll (Fig. 4C; not shown). Conversely, mis-expressing Ss (ptc-Gal4>UAS-ss) resulted in precocious Wg accumulation in L3 larvae that is first detected in the band of ptc-Gal4>ss-expressing cells (not shown) and then resolved to an antennal-like wedge pattern (Fig. 4D). This ss-dependent Wg activation starts in early L3 larvae, concomitant with and adjacent to endogenous dpp expression (not shown), and leads to earlier activation of Dll protein in the Mx field (not shown). These gain-of-function experiments strongly underline the capacities of Wg and Ss for mutual activation. Furthermore, both Wg and Ss direct a remarkably rapid reorganisation of the Mx territory towards an antennal primordium during L3 (Fig. 4C,D), though Wg seems more potent in this respect.

We therefore examined the relationship between wg and ss using loss-of-function mutations. Both affect maxillary development, as ss− homozygotes and adults deficient for wg signalling harbour reduced palps (Duncan et al., 1998) (and not shown). In ss− mutant pupae, Wg and Dll proteins accumulate at roughly normal levels in the Mx primordium (Fig. 4E,F). Conversely, when wg signalling was abolished via mitotic clones that eliminate the obligatory
pathway element *pygopus* (Belenkaya et al., 2002), Ss (Fig. 4G) and Dll (not shown) were absent from mutant *pygo* maxillary cells. The cell-autonomous loss of *ss* expression in *pygo* maxillary cells indicates that *wg* signalling is required for *ss* activation there. Although we have not directly tested the role of *dpp* signalling, these loss-of-function results support a model where *dpp/wg* signalling acts upstream of *Dll* and ss in the maxillary palp, as for other ventral appendages. Furthermore, in Mx *Dll* mutant clones, Ss is expressed normally (Fig. 4H). This suggests that, contrary to the antenna, Mx ss expression is independent of *Dll*.

In normal Mx development *wg* activates *ss*; the gain-of-function experiments further reveal that the Ss selector can activate *wg* via a positive-feedback loop. Together, these observations suggest that the transformation of maxillary-to-antenna induced by Ss may likewise require *wg* and that Wg is a central player in distinguishing Mx from antennal differentiation.

**wg controls the maxillary-versus-antenna identity choice via ss-dependent and -independent activities**

The complex interactions revealed by the preceding results led us to examine the relationship of *wg* and *ss* in maxillary/antennal development through functional tests of epistasis. In *ss* mutants, antennae are transformed to distal legs (Duncan et al., 1998) and maxillary palps are reduced relative to wild type (compare Fig. 5A1, 5A2), whereas *ptc*-directed *Wg*~*ss*~ (*wg~ss~*) induces a highly penetrant Mx-to-Ant transformation (Fig. 3B). Most double-mutant *wg~ss~/ss~* adults harbour a large nondescript maxillary outgrowth (Fig. 5A3). That the maxillary field can be re-directed by Wg to a leg in the *ss* condition suggests that mis-expressed Wg has reorganized the maxillary region into a permissive ‘pre-antennal’ environment whose transformation to antenna is blocked by the absence of *ss* activity (see Fig. 5G). We therefore examined the molecular organisation of *wg~ss~/ss~* larval E-A discs, using Dfd and Dan as Mx and antennal markers, respectively (Fig. 5B). Singly, *wg~ss~* (Fig. 3A, Fig. 5C) and *ss~go~* (Fig. 5D) induced a similar reorganisation of the Mx region to antenna, visible in L3 larvae by retraction of Dfd and de novo Dan and Dac accumulation (Fig. 5C,D; not shown). By contrast, in *wg~ss~/ss~* larvae, Dan was not observed in either the antennal or the maxillary field (Fig. 5E), correlating with the non-antennal adult Mx outgrowth (Fig. 5A3, A).

This indicates that mis-expressed Wg requires normal *ss* function to induce Dan and the subsequent antennal program. However, Dfd was reliably retracted from the budding ‘maxillary’ region of the same *wg~ss~/ss~* animals (Fig. 5E, arrowhead), similar to *wg~go~* alone (Fig. 5C). This retraction of Dfd indicates that Wg signalling can reorganise the Mx field independently of Ss.

In the reciprocal test, *pygo* clones were used to remove *wg* signalling activity from *ss~go~* tissues. No adults were obtained under these conditions, but Minute-enhanced *pygo* clones could be obtained in the antennal-maxillary region of *ss~go~* larvae (Fig. 5E,F’). As described above, *pygo* clones lead to inactivation of *ss* (Fig. 4G) and its target gene *dan* (not shown). In *ss~go~/pygo* double mutant cells, Dan was activated only in the narrow band of cells expressing Ss under the *ptc-Gal4* driver but not in the wider concentric rings typical of the Mx-to-antennal transformation (compare Fig. 5F with 5D), whereas normal Dfd expression persisted throughout the Mx field (Fig. 5F’). Ss protein is thus sufficient to induce Dan expression but requires *wg* signalling activity to achieve the Mx-to-Ant transformation, as seen by tissue morphology, molecular reorganisation of Dan-expressing regions and persistence of Dfd. Taken together, these results indicate that Wg provides a crucial input to the program initiated by Ss, but can also contribute to identity choice independently of Ss.

**DISCUSSION**

In this paper, we have analysed the regional specification of the antennal and the maxillary fields within the composite eye-antennal disc. This analysis shows that (1) a maxillary field leading to the adult Mx palp emerges in second instar larvae; (2) the specification and formation of the Mx primordium occurs in pre-pupae, i.e. much later than for other ventral appendages, via a program similar to that used to specify antennae; and (3) delayed Wg activation in the Mx field plays a crucial role, through *ss* or independently, in specifying Mx identity. We conclude that the temporal regulation of Wg is crucial in establishing Mx identity.

**The antennal imaginal disc is divided early into distinct but communicating antennal and maxillary territories**

Much previous attention for the eye-antennal disc has been directed towards the separation into eye and antennal fields (Domínguez and Casares, 2005; Kenyon et al., 2003; Kumar and Moses, 2001).
However, how the antennal region gives rise to both the antenna and the maxillary palp has not been addressed. We found that expression of Dfd (Mx) and Cut (Ant) define clonally separate antennal and maxillary fields of the antennal disc established by L2, at roughly the same time as the eye-antennal demarcation. Morata and Lawrence (Morata and Lawrence, 1979) showed that adult clones induced as late as L2 show that antennal and maxillary fates are determined independently at this stage.

Fig. 4. Wg and ss are functionally linked in maxillary/antennal programs. (A) In wild-type L3/pupal transition, Wg (green) and Ss (red) are expressed in the maxillary primordium of white prepupae. (B, C) Both Wg and Ss induce a maxillary-to-antennal transformation through a mechanism involving reciprocal activation. (D) In ssof L3 larvae (ptc-GAL4>UAS-wgts shifted to 18°C at 5 days AEL), Ss (red) is precociously induced on the band of Wg-expressing cells (green) within the neo-antennal territory (mx>a). (E) Clone of pygo– cells (no green GFP marker, outlined) where nuclear Ss protein (red) is cell-autonomously absent from mutant maxillary cells. (F) Clone of Dfd– cells (no green GFP marker, outlined) where nuclear Ss protein (red) is present in mutant maxillary cells. (E–F) These genotypes lead to reduction or loss of adult Mx palps (mx–). Antennal discs are oriented with posterior towards the right and dorsal towards the bottom; a and mx indicate antenna and maxillary primordia, respectively.

Fig. 5. Wg acts upstream of Ss and independently of it in transforming maxillary identity to antennal. (A, A1–A4) Light-microscope images of adult maxillary palps. (A1) Wild-type maxillary palps with their bordering row of bristles. (A2) ss–null homozygote shows strongly reduced maxillary palps. (A3) wggof; ss– double mutants (shifted to 18°C at 5 days AEL) generally have an enlarged structure, unlike either wggof neo-antennae or ss– stubs. These structures are positioned higher on the head, like neo-antennae (as seen in Fig. 3B). (A4) Same genotype as in A3, but with the maxillary palp replaced by distal leg with its distinctive claws. (B–E) Dan (green) and Dfd (red) expression in L3 E-A of (B) a wild-type antennal disc, (C) a wggof-induced transformation (ptc-GAL4>UAS-wgts shifted to 18°C at 5 days AEL), (D) a ss–induced transformation (ptc-GAL4>UAS-ss), (E) a wggof; ss– disc (shifted to 18°C at 5 days AEL) where Dfd (red) is excluded from the maxillary territory (arrowhead). (F, F) In ss– discs harbouring large pygo– clones (no GFP), Dan (red) is expressed in a narrow band of maxillary cells (arrowhead) and Dfd expression (red) is maintained (arrowhead). (G) Schematic summary of results. Antennal discs are oriented with posterior towards the right and dorsal towards the bottom; a and mx indicate antenna and maxillary primordia, respectively.
in the Mx field, we observed that the onsets of distinguishing Max/Ant identity primordium until the beginning of the pupariation. Activation, and thus the delay in a clear morphological maxillary ss in Fig. 2. In the antennal territory, the Hh targets genes and Mx programs show specific and divergent timelines as illustrated for the maxillary organ. The central players common to the antennal pathways and transcription factors: larval for the antenna and pupal about 1-2 hours after the L3/pupal stage (Fig. 4B). In culture conditions and reference wild-type stock, we first detect Dll delayed by roughly 12 hours, and are activated co-temporally, whereas in the maxillary field wg have been able to observe this delay in antennal cells appear to share this Hh source during L2, as (1) En/Hh interface presumably explains the late wg– ss– hh– dpp– signaling (not shown). These results concur with the conclusion of Emmons et al. (Emmons et al., 2007) that both are key players in distinguishing Mx from antennal identities.

A decisive role for Wg in organ identity
The similar Mx-to-ant transformations induced by Wg or Ss indicate that both are key players in distinguishing Mx from antennal identity. In normal Mx development, the onsets of nuclear Ss selector protein and diffusible Wg growth factor were temporally indissociable (Fig. 4A). Our results from loss-of-function experiments place wg signalling upstream of ss in the Mx primordium, as abolishing wg signal cell-autonomously silences ss (Fig. 4G), whereas wg is still expressed in the Mx primordium of a ss– mutant (Fig. 4E). However, the gain-of-function experiments show that ss can also activate wg by an autoregulatory loop (Fig. 4D). This suggests that wg provides an obligatory input in distinguishing Mx from Ant identities.

On confronting wgnull (Mx-to-ant) with loss of ss (stunted Mx), the resulting structures were unlike either (Fig. 5A), suggesting that Ss and Wg act at the same level. Importantly, mis-expressed Wg can reorganize the Mx territory in the absence of Ss. In most cases, this yields an undefined outgrowth (Fig. 5A2) and occasionally gives rise to a distal clawed leg in place of the Mx palp (Fig. 5A3). We infer
that the Mx-to-leg transformation seen for mis-expressed Wg in conjunction with ss reflects a Mx primordium that has already been reoriented toward a pre-antennal environment by the action of Wg (Fig. 5G). Accordingly, Dfd is seen to retract from the maxillary field of wggof, ss– larvae, as well as in the wggof alone (Fig. 5E,C). Wg is thus unable to activate Dan without ss but can confer anterolateral patterning characteristics correlated with the absence of Dfd. Conversely, ss is in any case sufficient to activate Dan, but without Wg it cannot induce Dfd retraction from the Mx field (Fig. 5F, F’). Thus, the absence of Dfd is not a simple consequence of Dan activation in the Mx field and reflects Wg activity. Taken together, these various results indicate that Wg can contribute to a tissue reorganisation involved in identity choice. Recent studies have implicated regulation of signalling pathways as an important element in identity choice, as dpp signalling regulated by Ultrabithorax in the haltere and by vestigial in the wing helps distinguish between these homologous structures (Crickmore and Mann, 2006; de Navas et al., 2006; Makhijani et al., 2007; Mohit et al., 2006).

The present work demonstrates that the timing of Wg expression is involved in distinguishing maxillary from antennal organs. Wg is well known as a potent mitogen, and we cannot exclude that its effect on tissue reorganisation and identity occurs at the level of cell proliferation (Kenyon et al., 2003; Serrano and O’Farrell, 1997). Nevertheless, as Wg exerts distinct effects on proliferation and patterning in the developing wing (Neumann and Cohen, 1996), these two aspects of Wg function appear to be separable. Similarly, Wg acts in specifying the wing primordium independently of its DV axis specification (Ng et al., 1996), and in distinguishing the eye primordium from the dorsal head vertex (Royet and Finkelstein, 1997). The novel role of Wg regulation in maxillary specification, where changing the temporal framework for this single signalling output incites maxillary cells to reorganise as an antennal organ, leads us to consider that the Wg morphogen acts not only as a DV axial factor but also as an identity determinant.

Appendage diversification

Appendage identity results from an interplay of regionalising signals and selector transcription factors such as Hox genes. No Hox selector gene is expressed in the antennal field, where identity has been attributed to the instructive quality of co-expressed Dll and Hth (Dong et al., 2000). Downstream Hth/Dll targets include ss and its own targets, dan and dan-related, which are required for antennal differentiation (Emerald et al., 2003; Suzanne et al., 2003). The Mx primordium also possesses the configuration thought to procure antennal identity: co-expression of Hth and Dll associated with Ss expression in the Dll-expressing cells (Fig. 2T, Fig. 4B). However, Ss-expressing cells of the antennal field activate dan, whereas Mx cells expressing Ss do not, raising the question what constitutes a cellular context refractory to dan activation? One possible explanation would be that the presence of Hox proteins in the Mx territory impedes dan expression there. The Mx region expresses two Hox proteins, Dfd and Pb, which might distinguish maxillary versus antennal identity. However, pb, Dfd or double mutant pb Dfd Mx primordia are not transformed to antenna and dan is not expressed there (not shown). These Hox selectors are not responsible for repressing dan expression in the Mx region, and thus they do not control the crucial steps distinguishing maxillary versus antennal programs. We propose a model where the pupal application of an antennal-like program in the Mx primordium prevents Ss-dependent dan activation there. This hypothesis is supported by the fact that precociously expressing Wg in the same territory is associated with premature Ss expression that induces Dan there. That dan can be activated in larval maxillary territory but not in pre-pupa suggests the existence of a larval competent stage (Fig. 6, green background) that is terminated in prepupae refractory to the same signal (Fig. 6, yellow background). Our working model supposes that Dfd contributes to elaborating Mx competence, and proposes that the primary signal of Mx specification is the delayed Wg expression in the prepupal stage (refractory to dan activation). Conversely, earlier maxillary expression of Wg in the competent stage of dan activation permits re-organisation toward antennal identity (Fig. 6, Mx-to-Ant).

A driving force in metazoan evolution may have been the diversification of regulatory paradigms for controlling morphogen activities to create distinct appendages. The delayed initiation of Wg uncoupled from dpp in the maxillary primordium is an unexpected situation for a ventral appendage, and suggests that strategies for uncoupling dpp from Wg may be important for diversifying developmental outcomes (Fig. 6). Our dissection of a novel program leading to a ventral appendage reveals that temporal regulation of signalling molecules may contribute to organ identity in as yet unexplored ways that help to create appendage diversity.

References

Wingless and maxillary identity


