Evidence for the temporal regulation of insect segmentation by a conserved sequence of transcription factors

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ABSTRACT

Long-germ insects, such as the fruit fly Drosophila melanogaster, pattern their segments simultaneously, whereas short-germ insects, such as the beetle Tribolium castaneum, pattern their segments sequentially, from anterior to posterior. While the two modes of segmentation at first appear quite distinct, much of this difference might simply reflect developmental heterochrony. We now show here that, in both Drosophila and Tribolium, segment patterning occurs within a common framework of sequential Caudal, Dichaete, and Odd-paired expression. In Drosophila these transcription factors are expressed like simple timers within the blastoderm, while in Tribolium they form wavefronts that sweep from anterior to posterior across the germband. In Drosophila, all three are known to regulate pair-rule gene expression and influence the temporal progression of segmentation. We propose that these regulatory roles are conserved in short-germ embryos, and that therefore the changing expression profiles of these genes across insects provide a mechanistic explanation for observed differences in the timing of segmentation. In support of this hypothesis we demonstrate that Odd-paired is essential for segmentation in Tribolium, contrary to previous reports.
INTRODUCTION

Arthropods have modular body plans, composed of distinct segments serially arrayed along the anterior-posterior (AP) axis. These segments are organised and maintained by a conserved network of "segment-polarity" genes, each of which is expressed in a segmentally-reiterated pattern of stripes (DiNardo et al. 1994; Damen 2002; Janssen & Budd 2013). Intriguingly, disparate developmental strategies are used across the arthropod phylum to generate this universal segmental pattern (Peel et al. 2005). For example, early developmental stages vary dramatically between "long-germ" and "short-germ" insect species (Krause 1939; Sander 1976; Davis & Patel 2002; Liu & Kaufman 2005), even though the insect body plan is largely invariant.

In long-germ embryos, e.g. those of the fruit fly Drosophila melanogaster, almost all segments are patterned during the blastoderm stage (Akam 1987; Nasiadka et al. 2002; Fig. 1A,B). Drosophila uses a bespoke set of “stripe-specific” enhancer elements, regulated by maternal and “gap” factors, to rapidly establish a spatially periodic pattern of “pair-rule” gene transcription factor expression (Schroeder et al. 2011). Pair-rule genes are expressed in patterns of seven regularly-spaced stripes, reflecting a transient double-segment periodicity within the Drosophila embryo (Nüsslein-Volhard & Wieschaus 1980; Hafen et al. 1984). At gastrulation, the positional information in the pair-rule pattern is used to pattern the segment-polarity genes, which are expressed in 14 stripes each (DiNardo & O’Farrell 1987; Bouchard et al. 2000; Clark & Akam 2016a).

In contrast, short-germ embryos, e.g. those of the beetle Tribolium castaneum, have retained the ancestral arthropod condition of patterning their segments sequentially from anterior to posterior over the course of embryogenesis (Patel et al. 1994; Patel 1994; Choe et al. 2006; Choe & Brown 2007). Short-germ embryos pattern only their anterior segments at the blastoderm stage; more posterior segments are patterned after gastrulation from a segment-addition zone (SAZ), in a process that is often coupled to embryo growth (Fig. 1A,C).

In Tribolium, periodic patterns do not arise from precise positioning of pair-rule stripes by gap gene orthologs (Lynch et al. 2012). Instead, the segmentation process involves sustained oscillations of pair-rule gene expression in the SAZ (Sarrazin et al. 2012; El-Sherif et al. 2012). Similar dynamic patterns of pair-rule gene expression are reported from spiders, myriapods, crustaceans, and other short-germ insects (for example: Schönauer et al. 2016; Brena & Akam...
These findings have drawn parallels with vertebrate somitogenesis – thought to occur via a "clock and wavefront" mechanism (Cooke & Zeeman 1976; Palmeirim et al. 1997; Oates et al. 2012), suggesting that pair-rule gene orthologs in short-germ arthropods are either components of, or entrained by, a segmentation clock (Stollewerk et al. 2003; Choe et al. 2006; Pueyo et al. 2008).

Although long-germ development is only found within holometabolous insects, the major orders within the Holometabola all contain both short-germ and long-germ species, suggesting that long-germ segmentation has evolved from a short-germ ancestral state several times independently (Davis & Patel 2002; Jaeger 2011). There is also at least one documented case of long-germ segmentation reverting to the short-germ state (Sucena et al. 2014). These frequent evolutionary transitions, added to the presence of numerous “intermediate” modes of development, argue that the regulatory changes required to transform a short-germ embryo to a long-germ embryo are not prohibitively complex. Consistent with this, comparisons of orthologous segmentation gene expression between long-germ and short-germ arthropods have revealed striking commonalities, suggesting that the overt differences might mask an underlying conservation of mechanism, particularly for the later parts of the process (Peel et al. 2005).

First, segmentation always involves pair-rule gene orthologs expressed periodically in time and/or space. Second, there is a conserved temporal progression from the expression of “primary” pair-rule genes (as defined by Schroeder et al. (2011); i.e., hairy, even-skipped, runt, odd-skipped (odd), and, in some species, fushi tarazu), to the expression of “secondary” pair-rule genes (i.e. paired (prd) and sloppy-paired (slp)), and finally the expression of segment-polarity genes (e.g., engrailed and wingless). In Drosophila, each stage of gene expression is observed only transiently (summarised in Fig. 1B); in Tribolium, the whole temporal sequence can be seen throughout the period of segment addition, as a posterior-to-anterior spatial pattern along the SAZ (summarised in Fig. 1C). Finally, key aspects of the overall patterning system seem to be conserved (Fig. 1E), such as a dynamic sequence of eve, runt, and odd expression at early stages (Choe et al. 2006; Clark 2017), and the use of partially overlapping prd and slp domains to establish parasegment boundaries (Green & Akam 2013).

These similarities between long-germ and short-germ segmentation could be explained if the patterning processes involved are fairly conserved, and it is mainly the timing of these processes relative to morphogenetic events that distinguishes the different modes of development (Patel et al. 1994; Akam 1994). This possibility is supported by our recent...
computational modelling study, which finds that the *Drosophila* pair-rule gene network can easily be modified into a clock and wavefront-type system capable of recapitulating both long-germ and short-germ expression dynamics (Clark 2017). The choice between these alternate macroscopic behaviours is specified, in the model, by the spatiotemporal expression patterns of extrinsic regulatory inputs which control the timing of state transitions within the pair-rule network.

Specifically, our model predicts that patterning networks in the blastoderms of long-germ insects function in the same way as those in the segment addition zones (SAZs) of short-germ insects, and that the evolution of long-germ segmentation involved heterochronic shifts in segmentation network deployment, mediated by changes to the expression patterns of key upstream regulatory factors. A similar evolutionary scenario has also been proposed recently by Zhu and colleagues (Zhu et al. 2017).

These theoretical proposals rest on two key predictions. First, there should exist broadly expressed factors that, via their influences on the segmentation network, control the temporal progression of the segmentation process. Second, the regulatory roles of these “timing factors” should be widely conserved, and therefore their expression patterns should remain tightly correlated with specific phases of segmentation gene expression across all insect embryos, regardless of whether they exhibit a long-germ or short-germ mode of development.

In this manuscript, we begin to test the predictions of our model. We first establish that, in *Drosophila*, the broadly-expressed segmentation genes *caudal*, *Dichaete*, and *odd-paired* are each associated with specific phases of segment patterning. We then show that, as predicted, the *Tribolium* orthologs of *caudal*, *Dichaete*, and *odd-paired* are expressed in the same temporal order, and preserve the same correlations with segmentation gene expression as are observed in *Drosophila*. However, while in *Drosophila* these factors are expressed ubiquitously throughout the trunk and thus provide only simple timers, in *Tribolium* they are expressed as retracting or advancing wavefronts, and thus could represent the primary source of spatial information within the short-germ segmentation process. Consistent with this interpretation, we find (in contrast to previous studies) that *Tc-opa* knockdown perturbs *Tribolium* segmentation. We also discover early developmental functions for *Tc-opa* in blastoderm formation and head patterning, which partially mask this segmentation role. Finally, we discuss the significance of our findings for the evolution of segmentation.
RESULTS

Candidates for conserved timing factors: Caudal, Dichaete, and Odd-paired

We define the term “segmentation timing factor” to mean a broadly-expressed but temporally restricted transcriptional regulator which participates in segment patterning by modulating the expression or function of canonical (spatially-patterned) segmentation genes.

Two such factors have already been identified: in Drosophila, the Zinc Finger transcription factor Odd-paired (Opa), which triggers the onset of segment-polarity gene expression at gastrulation (Benedyk et al. 1994; Clark & Akam 2016a), and, in Tribolium, the homeodomain transcription factor Caudal (Cad; Schulz et al. 1998; Macdonald & Struhl 1986), which is thought to quantitatively tune pair-rule and gap gene expression dynamics (El-Sherif et al. 2014; Zhu et al. 2017). In Drosophila, Cad directly activates posterior gap genes and primary pair-rule genes (Rivera-Pomar et al. 1995; Schulz & Tautz 1995; La Rosée et al. 1997; Hâder et al. 1998; Olesnicky et al. 2006). Another prime candidate is the SOX-domain transcription factor Dichaete (Russell et al. 1996; Nambu & Nambu 1996), which directly regulates primary pair-rule gene expression in Drosophila but does not noticeably affect gap gene expression (Russell et al. 1996; Ma et al. 1998; Fujioka et al. 1999; MacArthur et al. 2009; Aleksic et al. 2013).

We decided to use these three genes as a first test for our evolutionary hypothesis that insect segmentation occurs within a conserved – but spatiotemporally malleable – regulatory framework that determines where and when segment patterning networks will be deployed.

Sequential caudal, Dichaete, and odd-paired expression correlates with the temporal progression of Drosophila segmentation

We first characterised more precisely the associations of our three candidate timing factor genes with the various phases of Drosophila segmentation, using the pair-rule gene odd as a marker (Fig. 2A).

Following the staging scheme introduced in Clark & Akam (2016a), we divide pair-rule gene expression into three broad phases, spanning from early cellularisation to early germband extension (Fig. 1B). During phase I (early cellularisation), individual stripes of primary pair-rule gene expression are established by gap factors acting on stripe-specific enhancer elements, in most cases resulting in irregular/incomplete periodic patterns (Fig. ID, top).
During phase 2 (mid- to late-cellularisation), pair-rule factors cross-regulate through “zebra” elements, resulting in regular stripes of double-segment periodicity (Fig. 1D, bottom), and the secondary pair-rule genes turn on in the trunk. During phase 3 (gastrulation onwards), the regulatory network changes, and the expression patterns of some of the pair-rule genes (including odd) transition to single-segment periodicity.

We find that cad expression clears from the main trunk at the beginning of phase 2 (Fig. 2A). In contrast, Dichaete expression persists in the trunk throughout phase 2 (although it does become spatially modulated), clearing only at the beginning of phase 3. As described previously (Clark & Akam 2016a), opa expression builds up progressively, starting from phase 1. Antibody stains indicate that the dynamics of Cad and Dichaete protein expression closely reflect their respective transcript patterns (Macdonald & Struhl 1986; Ma et al. 1998), while Opa protein appears only after a significant delay (Benedyk et al. 1994), likely due to the length of its transcription unit, which contains a 14 kb intron (FlyBase). Segmentation in Drosophila therefore occurs against a changing background of transcription factor expression, with phase 1 characterised by both Cad and Dichaete, phase 2 mainly by Dichaete, and phase 3 by Opa (Fig. 2C).

caudal, Dichaete, and odd-paired expression correlates with segmentation timing differences along the anteroposterior axis

The expression of our candidate genes also correlates with the segmentation process across space. Although Drosophila segmentation is often described as “simultaneous”, three distinct regions along the AP axis undergo segment patterning at slightly different times (Fig. 2D; see also Surkova et al. 2008). In “region 1” (near the head-trunk boundary, encompassing odd stripe 1 and prd stripes 1 and 2), both primary and secondary pair-rule genes are expressed very early, and head-specific factors play a large role in directing gene expression (Schroeder et al. 2011; Andrioli et al. 2004; Chen et al. 2012). In “region 2” (the main trunk, encompassing odd stripes 2-6 and prd stripes 3-7), primary pair-rule genes turn on at phase 1, secondary pair-rules turn on during phase 2, and segment-polarity genes turn on at phase 3 (Fig. 1B). Finally, in “region 3” (the tail, encompassing odd stripe 7 and prd stripe 8), the expression of certain pair-rule genes is delayed, while segment-polarity gene expression emerges only during germband extension (Kuhn et al. 2000). This region of the fate map corresponds to parasegments 14 and 15, and eventually gives rise to the terminal segments (A9 and A10) and the anal pads (Campos-Ortega & Hartenstein 1985; Kuhn et al. 1995).
If our hypothesis is true, we would expect that spatial differences in the timing of segmentation also correlate with the expression patterns of our three putative timing factors. Indeed, this is what we find (Fig. 2B,D).

Region 1 never expresses cad or D, but does express opa, whose expression domain extends further anterior than those of the other two genes. Region 2 corresponds to the early broad domain of Dichaete expression, which extends from just behind odd stripe 1 to just behind odd stripe 6 (the opa expression domain shares the same posterior boundary). Finally, region 3 at first expresses only cad, as its domain extends further posterior than the other two genes. As development proceeds, region 3 transits through the same sequence of cad, D, and opa expression as was just described for the main trunk (Fig S1).

caudal retraction correlates with the onset of secondary pair-rule gene expression and is necessary for segment patterning

We have argued previously that the onset of Opa expression at phase 3 triggers expression pattern changes in Drosophila pair-rule and segment-polarity genes (Clark & Akam 2016a). We now briefly consider the functional significance of temporally-patterned Cad and Dichaete expression in Drosophila.

Transcription of the secondary pair-rule gene prd appears with a marked anterior-to-posterior and ventral-to-dorsal polarity (Kilchherr et al. 1986). While part of the reason for this is that the early expression of prd stripes 1+2 is under the control of a separate, Bicoid-dependent regulatory element (Gutjahr et al. 1994; Ochoa-Espinosa et al. 2005), the overall spatiotemporal pattern is still largely unexplained. Interestingly, the clearance of Cad protein from the embryo also occurs with both an anterior-to-posterior and ventral-to-dorsal polarity (Macdonald & Struhl 1986).

We therefore compared the expression of cad and prd in cycle 14 embryos and found that the emergence of the prd stripes is tightly spatiotemporally associated with retraction of cad expression (Fig. 3). This indicates that cad expression is specifically associated with early stages of segment patterning, before the secondary pair-rule genes turn on. While redundancy between maternal and zygotic cad contributions (Macdonald & Struhl 1986) demonstrates that segment patterning is fairly robust to quantitative variation in Cad expression, the temporal profile of Cad expression is evidently important. Cad misexpression is able to disrupt trunk segmentation when induced during the latter half of cellularisation (i.e., when the
secondary pair-rule genes are expressed), but not afterwards and not before (Mlodzik et al. 1990). This finding indicates that the clearance of cad expression at phase 2 is crucial for normal patterning.

Spatial regulation of prd is transiently compromised in Dichaete mutant embryos

Dichaete expression is lost from the trunk towards the end of cellularisation, therefore any direct effects on segmentation gene expression must occur prior to gastrulation. Of the seven pair-rule genes, hairy, eve, runt and ftz have been previously examined in Dichaete mutant embryos, and all have been found to show well-defined, albeit irregular, seven-stripe patterns during cellularisation (Russell et al. 1996; Nambu & Nambu 1996; Fig. S2,3). It is currently not clear whether these relatively subtle perturbations are caused simply by effects of Dichaete on pair-rule gene stripe-specific elements (Ma et al. 1998; Fujioka et al. 1999), or if Dichaete is additionally acting on pair-rule gene zebra elements.

We surveyed the expression of the remaining pair-rule genes, odd, prd, and slp, looking for any gross misregulation (Fig. S2,3). We found that all three genes are expressed in Dichaete mutant embryos, and turn on at the appropriate time, with normal DV polarity. For odd and slp we see again that their stripes are well-defined, although the widths and spacings are abnormal. The most noticeable patterning defect is a delay in the appearance of slp stripe 4 (arrowheads in Fig. S2), probably a downstream effect of an unusually broad runt stripe 3, which patterns its anterior border (Clark & Akam 2016a).

In contrast, early prd patterning is severely perturbed, with stripes 3-7 fused into a broad, aperiodic expression domain (Fig.4A). (prd stripes 1 and 2, which lie anterior to the Dichaete domain, develop normally.) prd trunk patterning recovers at later stages, as we see irregular “P” stripe domains (Gutjahr et al. 1994) emerge at late phase 2 (arrowheads in Fig. 4A), and finally a transition to a relatively normal segment-polarity pattern at phase 3. It therefore seems that Dichaete is specifically involved in the initial phase of prd regulation, when basic pair-rule periodicity is established.

This phase of prd regulation normally consists of direct repression from Eve: the early prd stripes are complementary with eve in wildtype, broaden somewhat in eve heterozygotes (Fig. 4B), fuse into a largely aperiodic expression domain in eve mutant embryos (Baumgartner & Noll 1990), and are rapidly repressed by Eve misexpression (Manoukian & Krause 1992). The early loss of prd periodicity in Dichaete mutant embryos resembles that in eve null embryos.
(Fig. 4B), consistent with the repression of prd by Eve requiring Dichaete expression. Other Eve pair-rule targets (ftz, odd, and slp) remain out of phase with the eve stripes in Dichaete mutant embryos (Fig. S3), rather than being ectopically expressed as in eve mutant embryos (see Clark 2017). This suggests that any functional interaction between Dichaete and Eve is specific to prd regulation.

The effect of Dichaete on prd expression presumably involves the prd zebra element and therefore implicates Dichaete as an extrinsic regulator of the pair-rule network analogous to Opa. As with Cad, heat-shock-mediated misexpression of Dichaete during cellularisation causes severe segmentation defects (Russell et al. 1996), indicating that an appropriate temporal profile of Dichaete expression is crucial for patterning. We can therefore conclude that Cad, Dichaete and Opa all temporally regulate the segmentation process in Drosophila, although the roles of Cad and Dichaete still need to be fully elucidated.

Staggered wavefronts of Tc-caudal, Tc-Dichaete, and Tc-odd-paired preserve the sequence of timing factor expression in the Tribolium SAZ

If long-germ segmentation does indeed represent a heterochronic shift in the deployment of a conserved patterning machinery, correlations between the expression patterns of our three putative timing factors and those of the canonical segmentation genes should be preserved in short-germ insects. We therefore examined the expression of their orthologs, Tc-cad, Tc-Dichaete, and Tc-opa, in the short-germ beetle Tribolium castaneum. The expression patterns of all three have been described previously (Schulz et al. 1998; Oberhofer et al. 2014; Choe et al. 2017; Zhu et al. 2017), but only for a few stages and not in combination, providing only a limited understanding of their spatiotemporal dynamics over the course of segmentation.

Fig. 5 shows staged expression of Tc-cad, Tc-Dichaete, and Tc-opa, all relative to a common marker, Tc-wg, over the course of germband extension. A more extensive set of stages is shown in Fig. S4, and direct comparisons between Tc-cad/Tc-Dichaete, Tc-cad/Tc-opa, and Tc-Dichaete/Tc-opa are shown in Fig. S5.

Tc-cad is continuously expressed in the SAZ, resulting in a persistent posterior domain that gradually shrinks over time as the germband elongates (a process that depends on convergent extension cell movements; Nakamoto et al. 2015; Benton et al. 2016). Tc-cad therefore turns off in presegmental tissues as they emerge from the anterior of the SAZ, well before the Tc-wg
stripes turn on. Faint pair-rule stripes of Tc-cad are sometimes seen in the anterior SAZ, paralleling similar stripes seen in Drosophila at early phase 3 (Fig. S6A,B).

Tc-Dichaete is also broadly expressed within the SAZ, but is excluded from the most posterior tissue, turning on slightly anterior to the terminal (circum-proctodea) Tc-wg domain. The SAZ expression of Tc-Dichaete extends slightly further to the anterior than that of Tc-cad, turning off just before the Tc-wg stripes turn on. Tc-Dichaete expression anterior to the Tc-cad domain tends to be at lower levels and/or periodically modulated; in some embryos we observe a separate stripe of Tc-Dichaete expression, anterior to the broad SAZ domain (Fig. 5G,H,K). Tc-Dichaete expression later transitions into persistent expression within the neuroectoderm, with expression now absent from the more lateral ectodermal regions. This same general sequence, from strong uniform expression, to weaker and periodically modulated expression, to neuroectodermal expression, is also observed in Drosophila development (Fig. 2A,B).

Finally, Tc-opa is absent from the posterior half of the SAZ, but is expressed in a broad posterior domain starting in the anterior SAZ and extending anteriorly to surround nascent Tc-wg stripes. The intensity of expression in this domain is spatially-modulated, with Tc-opa expression transitioning more anteriorly into relatively persistent segmental stripes, which cover the central third of each parasegment (Fig. S6D). A transition to segmental expression also occurs in Drosophila, during germband extension (Fig. S6C.)

Importantly, the overall pattern of expression is consistent throughout germband elongation: the posterior expression domains of each of the three genes retain the same relationship to the gross morphology of the embryo, and to each other, at each timepoint. This means that during germband elongation, each cell within the SAZ will at some point experience a temporal progression through the three transcription factors, similar to that experienced by cells within the Drosophila trunk over the course of cellularisation and gastrulation (compare Fig. 2). For most of the cells that contribute to the Tribolium trunk, this sequence is likely to start with Cad+Dichaete, transit through Dichaete+Opa, and end with Opa alone.
Correlations with segmentation gene expression are broadly conserved in *Tribolium*

We also compared the expression domains of *Tc-cad*, *Tc-Dichaete*, and *Tc-opa* to the expression patterns of key *Tribolium* segmentation genes (Fig. 6; and more extensive developmental series in Figs S7-S10). As expected, we found that the expression of each factor correlates with specific phases of segmentation gene expression, and that these correlations are very similar to those observed in *Drosophila*:

In *Drosophila*, we found that the onset of *prd* expression correlated with the retraction of *cad* expression (Fig. 3), and that the early, pair-rule phase of *prd* expression involved regulation by Dichaete (Fig. 4); in *Tribolium*, *Tc-prd* turns on near the anterior limit of the *Tc-cad* domain (Fig. 6A-C; Fig. S7), with the pair-rule phase of *Tc-prd* expression falling within the *Tc-Dichaete* domain, and stripe splitting occurring anterior to it (Fig. 6D-F; Fig. S8). In *Drosophila*, we found that the primary pair-rule genes turn on in the context of strong *Dichaete* expression (Fig. 2); in *Tribolium*, the *Tc-runt* pair-rule stripes turn on at the very posterior of the *Tc-Dichaete* domain, emanating from two lateral spots either side of the posterior *Tc-wg* domain (Fig. 6G-I; Fig. S9). The *Tc-eve* and *Tc-odd* stripes also emerge with similar dynamics (Fig. 6J-O; Fig. S10F-O; Sarrazin et al. 2012). Finally, in *Drosophila*, Opa is required for the frequency doubling of pair-rule gene expression and the activation of segment-polarity gene expression (Clark & Akam 2016a; Benedyk et al. 1994); in *Tribolium*, frequency doubling of all the pair-rule genes examined occurs within the *Tc-opa* domain, and the stripes of the segment-polarity genes *Tc-en* and *Tc-wg* emerge within it, as well (Fig. 6J-R; Fig. S10A-E).

The temporal progression of the segmentation process therefore seems to be remarkably similar in both species, albeit in a different spatiotemporal deployment: primary pair-rule genes are expressed dynamically in the context of Cad and Dichaete expression, secondary pair-rule genes turn on as Cad turns off, and frequency doubling and segment-polarity activation occur in the context of Opa expression.

**Parental RNAi for *Tc-opa* yields empty eggs and head patterning defects**

The expression patterns of *Tc-cad*, *Tc-Dichaete*, and *Tc-opa* are consistent with these three genes forming part of a conserved temporal framework that regulates insect segmentation. However, this hypothesis is not supported by existing *Tribolium* RNAi studies, which conclude
that Tc-opa is not involved in segmentation (Choe et al. 2006; Choe et al. 2017). In contrast, the iBeetle RNAi screen (Dönitz et al. 2015) does show severe pair-rule-like segmentation defects for Tc-opa consistent with our proposal. As a first pass screen, results from iBeetle need to be independently verified. We therefore performed our own Tc-opa RNAi experiments to clarify the situation. (For full results, see Tables SI-3.)

We first carried out parental RNAi (pRNAi) experiments using two non-overlapping fragments, corresponding to the 5’ and 3’ exons of the Tc-opa gene. The 5’ dsRNA injections resulted mainly in empty eggs (257/300; 86%) and very few wildtype cuticles (6/300; 2%). In contrast, the 3’ dsRNA injections resulted in a much smaller proportion of empty eggs (68/300; 23%) and many more wildtype cuticles (82/300; 38%), consistent with a weaker knockdown efficacy (Fig. 7A).

Importantly, cuticles showed similar minor segmentation defects in both pRNAi experiments, in particular a fusion between T3 and A1 (Fig. 7J-K'; Fig. S1I). However, severe segmentation defects were only seen in the 3’ pRNAi and accounted for <1% of the cuticles. Phenotypic cuticles showed a range of other defects, which were very similar in nature across the 5’ and 3’ experiments, relating to the antennae (twisted) and legs (often one bifurcated T2 appendage) (Fig. S1J2). Larvae with these relatively minor phenotypes often hatched, but exhibited abnormal movement and died before the first moult. Some cuticles exhibited more dramatic head patterning defects (loss of labrum, antennae and the head capsule; Fig. 8H-I'). These phenotypes were more common (as a percentage of total cuticles) and more severe (i.e., more with complete loss of head capsule) in the 5’ pRNAi experiment (Fig. 7B), consistent with the stronger effect 5’ dsRNA had on embryo viability relative to 3’ dsRNA.

Tc-opa is expressed broadly at blastodermal and pre-blastodermal stages

With respect to segmentation phenotypes, our pRNAi experiments yielded results not too dissimilar to those of Choe and colleagues. However, we were intrigued by the frequent head phenotypes in both our 3’ & 5’ pRNAi data and the iBeetle screen. We therefore analysed Tc-opa expression in blastoderm eggs, and discovered that strong Tc-opa expression prior to the appearance of the mandibular stripe had previously been overlooked.
We find that \textit{Tc-opa} is both maternally provided (ubiquitous mRNA at pre-blastoderm stages, Fig. 8A) and zygotically expressed at high levels in the earliest blastoderm stages (Fig. 8B-F), at first ubiquitously (Fig. 8G), but resolving towards the end of the uniform blastoderm stage into a wedge-shaped region covering the future anterior head anlagen (Fig. 8H-K). These early expression domains could explain the high levels of embryonic lethality and/or head phenotypes resulting from our pRNAi injections. The RNAi defects associated with appendages (i.e. antennae and legs) also correlate with specific \textit{Tc-opa} expression domains (Fig. 5P-R), such that overall there is a tight association between the cuticle defects we observe following RNAi and the numerous domains of \textit{Tc-opa} expression.

Embryonic RNAi for \textit{Tc-opa} reveals an important role in segmentation

We hypothesized that a critical blastoderm role for Opa might arrest development at early stages in eggs where \textit{Tc-opa} is strongly knocked down, precluding the appearance of severe segmentation phenotypes in our pRNAi experiments and in those of Choe and colleagues. Consistent with this idea, fixations of 48-hour (30°C) egg collections from 5' pRNAi females revealed very few germband stage embryos (7/311; 2%) compared to controls (459/669; 67%). DAPI staining of the germband-less eggs revealed that very few had reached the blastoderm stage (1/50; 2%) but many had commenced nuclear divisions (34/50; 68%), indicating that embryonic development was starting, but usually stalling before the blastoderm stage (Fig. S13).

To bypass these early roles of \textit{Tc-opa} in embryogenesis, we decided to perform embryonic RNAi (eRNAi), using the same 5' and 3' dsRNA fragments. Egg injections of \textit{Tc-opa} dsRNA were carried out at pre-blastoderm to early blastoderm stage (2-4 hours AEL as measured at 30°C), alongside control injections of buffer. In agreement with our supposition that early \textit{Tc-opa} expression is necessary for development, the prevalence of empty eggs resulting from these injections (3': 80/198; 40%, and 5': 117/252; 46%) was relatively low compared to 5' pRNAi (257/300; 86%), and not that much higher than observed in control embryonic injections (55/198; 28%).
Strikingly, the proportion and severity of segmentation phenotypes increased dramatically with eRNAi compared to pRNAi (Fig. 7C). We observed a phenotypic series in segmentation defects, ranging from local segment fusions (Fig. 7L-M') as seen in the pRNAi experiments, through to canonical pair-rule phenotypes (Fig. 7N,O) as reported in the iBeetle screen, and finally compacted balls of cuticle or cuticle fragments, sometimes with only a hindgut remaining (Fig. S14). In the thorax, the fusions always involved the loss of odd-numbered segment boundaries (Fig. 7D), just as seen in opa mutant cuticles in *Drosophila* (Jürgens et al. 1984; Benedyk et al. 1994). Fusions in the abdomen were typically more extensive, involving both odd-numbered and even-numbered boundaries. The 5’ & 3’ eRNAi phenotypes were very similar in type and frequency, ruling out off-target RNAi effects, and their relative absence from injection controls and similarity to pRNAi phenotypes argues against injection artefacts (Fig. S11,12; Tables S1-S3). Taken together, these results indicate that opa is indeed (in addition to many other roles) a segmentation gene in *Tribolium*, and that its segment patterning role is likely at least partially conserved between long-germ and short-germ insects.

**Surviving Tc-opa pRNAi germbands exhibit a range of defects correlated with cuticle phenotypes**

The appearance of strong head phenotypes but not strong segmentation phenotypes in our pRNAi experiments suggests that the head patterning function of *Tc-opa* is more sensitive to RNAi than both the blastoderm and segmentation functions. Indeed, when we examined pRNAi germbands (Fig. 8M-P), we found several with much reduced head lobes (presumably corresponding to the head phenotypes observed in the cuticles) and these had essentially normal segmental *Tc-wg* expression. We also observed a loss of antennal *Tc-wg* expression, and an asymmetric ectopic stripe of *Tc-wg* expression within the second thoracic segment, correlating with antennal abnormalities and T2 leg bifurcations respectively (Fig. S12 J-O).

In these pRNAi embryos, cytoplasmic *Tc-opa* expression was largely absent, indicating that the RNAi had at least been partially effective. However, the embryos exhibited very strong nuclear dots (Fig. 8N'), indicating that *Tc-opa* was being transcribed at high levels, and might be hard to knock down completely using pRNAi. In addition, although the *Tc-wg* stripes in these embryos indicated successful segment boundary formation, the germbands were shorter and fatter than wildtype and the pattern of *Tc-opa* expression was abnormal. These observations indicate that subtle AP patterning defects (such as convergent-extension problems and
segment-polarity abnormalities) occur even in partial knockdowns, perhaps explaining the local segment fusions we observed in pRNAi cuticles.

DISCUSSION

We have found that segment patterning in both *Drosophila* and *Tribolium* occurs within a conserved framework of sequential Caudal, Dichaete, and Odd-paired expression. In the case of Opa, we also have evidence for conserved function. However, while the sequence itself is conserved between the two insects, its spatiotemporal deployment across the embryo is divergent (Fig. 9A). In *Drosophila*, the factors are expressed ubiquitously within the main trunk, and each turns on or off almost simultaneously, correlating with the temporal progression of a near simultaneous segmentation process. In *Tribolium*, their expression domains are staggered in space, with developmentally more advanced anterior regions always subjected to a “later” regulatory signature than more posterior tissue. These expression domains retract over the course of germband extension, correlating with the temporal progression of a sequential segmentation process built around a segmentation clock.

Orchestration of complex developmental processes by extrinsic timing factors

Pair-rule patterning involves several distinct phases of gene expression, each requiring specific regulatory logic (Clark & Akam 2016a). We propose that, in both long-germ and short-germ species, the whole process is orchestrated by a series of key regulators, expressed sequentially over time, three of which we have focused on in this manuscript. By rewiring the regulatory connections between other genes, factors like Dichaete and Opa allow a small set of pair-rule factors to carry out multiple different roles, each specific to a particular spatiotemporal regulatory context. This kind of control logic makes for a flexible, modular regulatory network, and may therefore turn out to be a hallmark of other complex patterning systems.

Having highlighted the significance of these “timing factors” in this manuscript, the next steps will be to investigate their precise regulatory roles and modes of action. It will be interesting to dissect how genetic interactions with pair-rule factors are implemented at the molecular level. Dichaete is known to act both as a repressive cofactor (Zhao & Skeath 2002; Zhao et al. 2007) and as a transcriptional activator (Aleksic et al. 2013), therefore a number of different mechanisms are plausible. The Odd-paired protein is also likely to possess both these kinds of regulatory activities (Ali et al. 2012).
Conserved temporal regulation of insect segmentation?

Given the phylogenetic distance between beetles and flies (separated by at least 300 million years, Wolfe et al. 2016), we expect that the similarities we see between *Drosophila* and *Tribolium* segmentation are likely to hold true for other insects, and perhaps for many non-insect arthropods as well. We propose that these similarities, which argue for the homology of long-germ and short-germ segmentation processes, result from conserved roles of Cad, Dichaete, and Opa in the temporal regulation of pair-rule and segment-polarity gene expression during segment patterning. This hypothesis can be tested by detailed comparative studies in various arthropod model organisms.

Above, we provided evidence that a segmentation role for Opa is conserved between *Drosophila* and *Tribolium*, while clear segmentation phenotypes have been found for Cad in *Nasonia* (Olesnicky et al. 2006) and Dichaete in *Bombyx* (Nakao 2017). However, as our *Tc-opa* experiments revealed, functional manipulations in short-germ insects will need to be designed carefully in order to bypass the early roles of these pleiotropic genes. For example, *cad* knockdowns cause severe axis truncations in many arthropods (Copr et al. 2004), while *Dichaete* knockdown in *Tribolium* yields mainly empty eggs (Oberhofer et al. 2014).

Opa is a key developmental transcription factor in *Tribolium*

It was previously thought that *Tc-opa* was not required for segmentation (Choe et al. 2006; Choe et al. 2017), and that the segmentation role of Opa may have been recently acquired, in the lineage leading to *Drosophila* (Choe & Brown 2007). However, our analysis reveals that *Tc-opa* is indeed a segmentation gene, and also has other important roles, including head patterning and blastoderm formation. Given that a similar developmental profile of *opa* expression is seen in the millipede *Glomeris* (Janssen et al. 2011), and even in the onychophoran *Euperipatoides* (Janssen & Budd 2013), we think that the segmentation role of Opa may actually be ancient.

Head phenotypes following *Tc-opa* RNAi were unexpected, but both the blastoderm expression pattern and cuticle phenotypes we observe are strikingly similar to those reported for *Tc-otd* and *Tc-ems* (*Tribolium* orthologs of the *Drosophila* head ‘gap’ genes *orthodenticle* and *empty spiracles*; Schinko et al. 2008), suggesting that the three genes function together in a gene network controlling early head patterning. This function of *Tc-opa* might be
homologous to the head patterning role for Opa discovered in the spider *Parasteatoda* (Kanayama et al. 2011), where it interacts with both Otd and Hedgehog (Hh) expression. Opa/Zic is known to modulate Hh signalling (Koyabu et al. 2001; Chan et al. 2011; Quinn et al. 2012), and a role for Hh in head patterning appears to be conserved across arthropods, including *Tribolium* (Farzana & Brown 2008; Hunnekuhl & Akam 2017).

Finally, Opa/Zic is also known to modulate Wnt signalling (Murgan et al. 2015; Pourebrahim et al. 2011). In chordates, Zic expression tends to overlap with sites of Hh and/or Wnt signalling, suggesting that one of its key roles in development is to ensure cells respond appropriately to these signals (Fujimi et al. 2012; Sanek et al. 2009; Chervenak et al. 2013; Houtmeyers et al. 2013). The expression domains of *Tc-opa* that we observe in *Tribolium* (e.g., in the head, in the SAZ, and between parasegment boundaries) accord well with this idea.

**The evolution of arthropod segmentation**

Similar embryonic expression patterns of Cad, Dichaete and Opa orthologs are observed in other bilaterian clades, including vertebrates. Cdx genes are expressed in the posterior of vertebrate embryos, where they play crucial roles in axial extension and Hox gene regulation (van Rooijen et al. 2012; Neijts et al. 2016). Sox2 (a Dichaete ortholog) has conserved expression in the nervous system, but is also expressed in a posterior domain, where it is a key determinant of neuromesodermal progenitor (posterior stem cell) fate (Wood & Episkopou 1999; Wymeersch et al. 2016). Finally, Zic2 and Zic3 (Opa orthologs) are expressed in presomitic mesoderm and nascent somites, and have been functionally implicated in somitogenesis and convergent extension (Inoue et al. 2007; Cast et al. 2012). All three factors thus have important functions in posterior elongation, roles which may well be conserved across Bilateria (Copf et al. 2004).

In *Tribolium*, we think that all three factors may be integrated into an ancient gene regulatory network downstream of posterior Wnt signalling, which generates their sequential expression and helps regulate posterior proliferation and/or differentiation (McGregor et al. 2009; Oberhofer et al. 2014; Williams & Nagy 2016). For example, it is suggestive that we observe mutually exclusive patterns of *Tc-wg* and *Tc-Dichaete* in the SAZ: Wnt signalling and Sox gene expression are known to interact in many developmental contexts (Kormish et al. 2010), and these interactions may form parts of temporal cascades (Agathocleous et al. 2009).
We therefore suggest the following outline as a plausible scenario for the evolution of arthropod segmentation (Fig. 9B):

(1) In non-segmented bilaterian ancestors of the arthropods, Cad, Dichaete and Opa were expressed broadly similarly to how they are expressed in *Tribolium* today, mediating conserved roles in posterior elongation, while gap and pair-rule genes may have had functions in the nervous system (Isshiki et al. 2001; Doe et al. 1988; Mondal et al. 2007; Shimojo et al. 2008; Janssen & Budd 2013).

(2) At some point, segmentation genes came under the regulatory control of these factors, which provided a pre-existing source of spatiotemporal information in the developing embryo. Pair-rule genes began oscillating in the posterior, perhaps under the control of Cad (El-Sherif et al. 2014; Schönauer et al. 2016) and/or Dichaete, while the posteriorly retracting expression boundaries of the timing factors provided smooth wavefronts that effectively translated these oscillations into periodic patterning of the AP axis, analogous to the roles of the opposing retinoic acid and FGF gradients in vertebrate somitogenesis (Oates et al. 2012).

(3) Much later, in certain lineages of holometabolous insects, the transition to long-germ segmentation occurred. This would have involved two main modifications of the short-germ segmentation process: (A) changes to the expression of the timing factors, away from the situation seen in *Tribolium*, and towards the situation seen in *Drosophila*, causing a heterochronic shift in the deployment of the segmentation machinery from SAZ to blastoderm, and (B) recruitment of gap genes to pattern pair-rule stripes, via the ad hoc evolution of stripe-specific elements (Peel & Akam 2003; Rosenberg et al. 2014).

The appeal of this model is that the cooption of existing developmental features at each stage reduces the number of regulatory changes required to evolve de novo, facilitating the evolutionary process. Note that under this scenario arthropod segmentation would not be homologous to segmentation in other phyla, but would probably have been fashioned from common parts (Chipman 2010; Graham et al. 2014).
METHODS

_Drosophila melanogaster_

Embryo collections were carried out at 25° C. The _Drosophila_ mutants used were _D^r72_ (gift of Steve Russell) and _eve^3_ (gift of Bénédicte Sanson). Wildtype flies were Oregon-R. In order to distinguish homozygous mutant embryos, mutant alleles were balanced over _CyO hb::lacZ_ (Bloomington stock no. 6650). DIG-labelled and FITC-labelled riboprobes were generated using full-length cDNAs from the _Drosophila_ gene collection (Stapleton et al. 2002), obtained from the _Drosophila_ Genomics Resources Centre. The clones used were LD29596 (_cad_), LD16125 (_opa_), MIP30861 (_eve_), IP01266 (_runt_), GH22686 (_ftz_), RE48009 (_odd_), GH04704 (_prd_), LD30441 (_slp_), and FI07617 (_en_). The cDNA for _Dichaete_ was a gift from Steve Russell, and the cDNA for _lacZ_ was a gift from Nan Hu.

Double fluorescent in situ hybridisation was carried out as described previously (Clark & Akam 2016a). Images were acquired using a Leica SP5 confocal microscope. Contrast and brightness adjustments of images were carried out using Fiji (Schindelin et al. 2012; Schneider et al. 2012). Some of the wildtype images were taken from a previously published dataset (Clark & Akam 2016b).

*Tribolium castaneum*

Whole mount in situ hybridisation:

_Tribolium castaneum_ eggs (San Bernardino strain) were collected on organic plain white flour (Doves Farm Foods Ltd, Hungerford, U.K.) at 30°C over a period of 48 hours. Alkaline phosphatase in situ hybridization on whole mount embryos were carried out as previously described (Schinko et al. 2009). RNA probes were DIG-labelled (all genes) and in most cases also FITC-labelled (_Tc-Dichaete_, _Tc-opa_, _Tc-prd_, _Tc-wg_ & _Tc-en_) and prepared according to Kosman et al. (2004), using gene fragments amplified from _Tribolium castaneum_ genomic DNA (for _Tc-cad_, _Tc-eve_, _Tc-odd_ & _Tc-run_) or cDNA (for _Tc-Dichaete_, _Tc-opa_, _Tc-prd_, _Tc-wg_ & _Tc-en_) and cloned into the pGEM-T Easy Vector (Promega, Madison, WI). Clones, and their details, are available on request.
The generation of DIG-labelled probes against Tc-cad has been previously described in Peel & Averof (2010), and the generation of DIG-labelled probes against Tc-eve and Tc-odd has been previously described in Sarrazin et al. (2012). The remaining gene fragments were amplified using the following primers: Tc-run: 5'-CAACAAGAGCCTGCCCATC-3' & 5'-TACGGCCTCACACACTTT-3' (amplifies 3,158 bp fragment). Tc-Dichaete (TC013163): 5'-TAACAACCGACACCCACAG-3' & 5'-TTGACGACCACAGCTACAAATAA-3' (921 bp fragment). Tc-opa (TC010234): 5'-CCCAAGAATGGGCTACTGC-3' & 5'-TTGAAGGGCCTCCCGTT-3' (710 bp 5' fragment), 5'-GCGAGAAGGCCGTTCAAAT-3' & 5'-TCTCTTTATACATGTTGTCCTAC-3' (705 bp 3' fragment); two probes made separately and combined. Tc-prd: 5'-GAATACGGCCCTGTGTTATCT-3' & 5'-ACCGCATGTACGGCTGATGT-3' (1179 bp fragment). Tc-wg: 5'-CCCAAGAATGGGCTACTGC-3' & 5'-TTGAAGGGCCTCCCGTT-3'. Tc-en: 5'-TGCAAGTGGGCTGATGT-3' & 5'-GCAACTAGGATTGTGCCTTC-3' (1001 bp fragment).

In the double in situ hybridizations where Tc-cad mRNA is detected in red, the primary antibodies were switched such that anti-DIG-AP was used second (after anti-FITC-AP) to detect Tc-cad DIG probe, and signal developed using INT/BCIP (see Schinko et al. (2009) for more details). Embryos were imaged on a Leica M165FC Fluorescence Stereo Microscope with a Q Imaging Retiga EXI colour cooled fluorescence camera and Q Capture Pro 7 software.

RNA interference (RNAi):

The Tc-opa gene is composed of two exons separated by a large 19.5 kb intron. A 710 bp DNA fragment corresponding to the 1st exon (i.e. template for 5' dsRNA) was amplified by PCR from Tribolium cDNA using the following primer pair: 5'-CCCAAGAATGGGCTACTGC-3' and 5'-TTGAAGGGCCTCCCGTT-3'. Similarly, a 705 bp DNA fragment corresponding to the 2nd exon (i.e. template for 3' dsRNA) was amplified using the following primer pair: 5'-GCGAGAAGCGTCTCAAAT-3' and 5'-TCTCTTTATACATGTTGTCCTAC-3'. These DNA fragments were cloned into the pGEM-Teasy vector (Promega) and antisense and sense ssRNA was produced using the T7 and SP6 MEGAscript High Yield Transcription Kits (Ambion). Antisense and sense ssRNA was then annealed in equimolar amounts, and diluted, to produce 1 μg/μl stocks of Tc-opa 5' and 3' dsRNA; these were aliquoted and stored at -20°C ready for future use.
Adult parental RNAi (pRNAi) was carried out using well-established protocols (Posnien et al. 2009). In the first round of pRNAi experiments, 250 females were injected with 5' Tc-opa dsRNA, 245 females were injected with 3' Tc-opa dsRNA, and the two sets of parallel injection controls each involved injecting 240 females with control buffer. In the 2nd round of pRNAi experiments, 100 females were used in each treatment (see Table S1 for more details). Following injection and a 2-day recovery, 48 or 72-hour egg collections were obtained in white flour at regular intervals, with beetles ‘rested’ for 24 hours on nutrient-rich wholemeal flour in between each egg collection. Roughly half of the eggs were immediately fixed for expression analysis, while the remainder were kept and allowed to develop for cuticle preparations. Embryonic RNAi (eRNAi) was performed by lightly bleaching 1-3 hour old eggs for 90 seconds in a 5% thin bleach solution. The eggs were then transferred to a microscope slide (circa 60) and lined up along one edge of the slide ready for injection. Eggs were orientated so that they could be injected into the posterior pole, perpendicular to the egg axis, in rapid sequence. Eggs were injected with dsRNA or buffer using pulled needles made from borosilicate glass capillaries (Harvard Apparatus; GC100F-10; Part No. 30-0019). The needles were pulled using a Narishige needle puller (Model PD-5), with the needle sharpened and standardized as much as possible using a Narishige needle grinder (Model EG-45). Injections were carried out on a Zeiss Axiovert 10 inverted microscope, using a continuous flow injection set up.
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COMPETING INTERESTS

The authors declare that no competing interests exist.
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Fig. 1. Comparison of long-germ and short-germ segmentation. (A) Developmental timelines for *Drosophila* and *Tribolium*. Hours until blastoderm-to-germband transition and full germband extension at 25°C are marked. Grey=embryonic territory. (B) Overview of *Drosophila* pair-rule patterning. Key stages of primary pair-rule, secondary pair-rule, and segment-polarity gene expression are shown in embryos of increasing age. (C) Overview of *Tribolium* pair-rule patterning, depicting equivalent gene expression in an embryo at mid
germband extension. Red/grey boxes highlight similarities with the Drosophila patterns, left. Overview of the segment addition zone (SAZ) at top. (D) Enhancer organisation of odd-skipped (Schroeder et al. 2011), with relevant expression output highlighted above. (E) Conserved patterns of gene expression across arthropod segmentation (see text).
Fig. 2. Spatiotemporal dynamics of cad, Dichaete, and opa during Drosophila segmentation. (A) Expression relative to odd. (B) Expression relative to each other. (C) Summary of overall temporal sequence. (D) Spatial correlations with segmentation timing differences along the AP axis. Embryos are all at early phase 2; annotations highlight distinct regions of pair-rule gene expression (see text); bottom right panel combines two embryos from (B). Some opa/odd images in (A) are from Clark and Akam (2016a). Scale bar = 100 µm.
Fig. 3. *cad* and *prd* exhibit complementary spatiotemporal dynamics. Phase 1: the *prd* stripe 1+2 domain directly abuts *cad* expression in the trunk. Phase 2: *prd* stripes 3-7 emerge as *cad* expression retracts posteriorly and dorsally. Phase 3: *prd* stripe 8 (asterisk) emerges as the *cad* tail domain retracts posteriorly. Arrowheads mark the posterior border of *prd* stripe 7. Scale bar = 100 µm.
**Fig. 4.** prd expression is perturbed in *Dichaete* mutant embryos. (A) Ectopic prd expression is present at early phase 2 in *Dichaete* mutants. Enlarged views show stripes 3-6. Note that prd and eve expression overlaps at all stages in *Dichaete* mutants, but only at later stages in wildtype. Arrowheads mark “P” stripes. (B) prd expression is aperiodic throughout phase 2 in eve mutants, but only at early phase 2 *Dichaete* mutants. Scale bars = 50 µm. “ph.” = phase.
Fig. 5. Spatiotemporal dynamics of Tc-cad, Tc-Dichaete, and Tc-opa during Tribolium segmentation. Germ band age increases from left to right; columns are stage-matched by Tcw expression (Mn=mandibular; T1=prothoracic; A1/4/7=1st/4th/7th abdominal). Blue arrowheads (G,H,K) indicate a Tc-Dichaete stripe anterior to the strong posterior expression domain. Black arrows (P-Q) mark Tc-opa expression in the antennae and at the bases of the thoracic legs. Scale bars = 100 µm.
Fig. 6. Expression of Tc-cad, Tc-Dichaete, and Tc-opa relative to selected segmentation genes. (A-F) The 4th Tc-prd primary pair-rule stripe forms at the anterior of the Tc-cad (A, B) and Tc-Dichaete (D,E) domains, and splits to form segmental stripes (4a & 4b) anterior to these domains (C, F). (G-I) The 4th and 5th Tc-run primary pair-rule stripes form at the posterior of the Tc-Dichaete domain, while the 2nd primary stripe splits anterior to the Tc-Dichaete domain. (J-O) The 4th and 5th Tc-odd/Tc-eve primary pair-rule stripes form posterior to the Tc-opa domain, while the 3rd Tc-odd/Tc-eve primary pair-rule stripes resolve into segmental stripes (3a & 3b) within the Tc-opa domain. (P-R) The T3 and A1 Tc-en stripes form within Tc-opa domain. Nascent segmental stripes (solid arrowheads) emerge from a region
where *Tc-opa* expression is already clearing (empty black arrowhead). Blue arrowheads (A-O) mark resolving or recently resolved segmental stripes; colour-coded lines (A-I) indicate the extent of expression domains. Scale bars = 50 µm.
Fig. 7. Tc-opa RNAi reveals head and segmentation roles. (A) Summary results for pRNAi and eRNAi, compared to sham-injected controls. (B-C) Quantification of head and segmentation phenotypes following RNAi. (pRNAi data are from a different experiment to (A), see Table S1.) (D) Counts of RNAi-induced local segment fusions within the thorax (all experiments). (E-G, P) Wildtype larval cuticles. (H-I') Representative larval cuticles with RNAi-induced head phenotypes. (J-P) Representative larval cuticles with RNAi-induced segmentation phenotypes. Blue (thoracic) and red (abdominal) circles in (K', M', P) highlight the relative position of homologous bristles. Scale bars = 100 μm. See Tables S1-3 and Figs S11, S12, S14 for more details.
Fig. 8. *Tc-opa* expression in wildtype blastoderms and *Tc-opa* RNAi germbands. (A-C). *Tc-opa* mRNA in early embryos. Eggs in each panel were imaged simultaneously, all panels use the same microscope/camera settings. (D) High resolution image of the egg in (F), revealing nascent nuclear *Tc-opa* transcripts (“nuclear dots”) in energids surfacing to form the blastoderm. (E-L’) Blastoderm eggs of increasing age stained for *Tc-opa* (E-L, blue) and *Tc-wg* (I-L, red), staged using DAPI staining (E’-L’). (M-P) Germband stage embryos from *Tc-opa* RNAi females stained for *Tc-opa*, compared to controls from sham-injected females (*Tc-wg*, red, used for stage-matching). Note reduced head lobes and punctate *Tc-opa* expression (N’), reflecting reduced transcript levels in the cytoplasm and strong nuclear dots. Black arrow (O) indicates antennal *Tc-opa* and *Tc-wg* domains, missing from (P). Coloured bars (O,P) highlight an altered segment-polarity pattern in (P). Scale bars = 100 µm.
Fig. 9. A conserved regulatory framework for arthropod segmentation. (A) Schematic comparison of timing factor expression during *Drosophila* versus *Tribolium* segmentation. Kymographs depict expression along the ectodermal AP axis over time. Dotted lines mark blastoderm-to-germband transition. Neural and segment-polarity expression domains are not drawn. (B) Proposed scenario for the evolution of arthropod segmentation (see text).
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A

B

C

D

Figure A: Images showing the expression patterns of cad, Dichaete, opa, and odd in different developmental phases.

Figure B: Diagram illustrating the expression of cad, Dichaete, opa, and odd.

Figure C: Images of opa and cad expression patterns in early and mid phases.

Figure D: Images of ftz and cad expression patterns.
Fig. S1. Shifting boundaries of timing factor expression within the Drosophila tail.

(A) Cropped and rotated enlargements of the odd stripe 7 region, at three timepoints (equivalent to the 3 penultimate rows in 2A,B.) (B) Schematic diagram of the shifting expression domains within the tail, based on the images in (A). Expression boundaries of cad, Dichaete, and opa shift posteriorly across odd stripe 7 over time. The anterior boundary of odd stripe 7 is assumed to be static (Surkova et al. 2008; Clark & Akam 2016). (C) Nascent transcription (nuclear dots, marked by arrowheads) of opa expression are observed within the cad domain throughout gastrulation and early germband extension, indicating that the opa expression domain is expanding posteriorly. (D) The cad posterior domain shifts markedly relative to stripe 7 of ftz over time. Cropped and rotated enlargements of the stripe 7 region are show below the whole embryo views. The bright red regions of staining in (D) outside of the cad posterior domain are artefacts caused by bits of debris stuck to the embryos. Scale bars = 50 µm.
**Fig. S2. Pair-rule gene expression in *Dichaete* mutant embryos.**

Embryos are at late phase 2. In all cases, pair-rule periodicity is still present in the mutants, but stripes are irregular in width and intensity. Expression patterns are broadly consistent across stage-matched embryos. Arrowheads point to a weak/delayed slp stripe 4.
Fig. S3. Relative phasing of pair-rule stripes in *Dichaete* mutant embryos. Embryos are at late phase 2. Expression patterns of repressors (magenta) are shown relative to those of their target genes (green). (For a description of the pair-rule network, see Clark (2017).) In most cases (e.g., *eve* versus *ftz/odd/slp*, or *runt* versus *slp*), the relative phasing of the stripes is preserved, suggesting that cross-regulatory interactions are operating normally. Only the phasing of *runt* expression relative to *hairy* and *odd* is clearly abnormal. Scale bars = 50 µm.
**Fig. S4.** Expression of *Tc-cad*, *Tc-Dichaete*, and *Tc-opa* relative to a common segment marker, *Tc-wg*, in *Tribolium castaneum* germband stage embryos.

(A-U). Sets of three *Tribolium castaneum* germband stage embryos that have been stage matched using *Tc-wg* expression patterns (*Tc-wg* expression brown in all panels). Stage-matched germband embryos increase in age from A to U. In each set of embryos, the left-hand embryo is also stained for *Tc-cad* expression, the middle embryo is stained for *Tc-Dichaete* expression and the right-hand embryo is stained for *Tc-opa* expression (all blue stains). In the double in situ hybridizations for *Tc-cad* & *Tc-wg* (left-hand embryos) the mandibular (Mn), prothoracic (T1), 1st abdominal (A1), 4th abdominal (A4), 7th abdominal (A7) and/or 10th abdominal (A10) stripes of *Tc-wg* expression have been labeled. Note how the relative position of the expression domains of these three genes is remarkable conserved across progressive germband elongation stages. Consult Fig. 5 for a clear comparison across different developmental stages, rather than between *Tc-cad*, *Tc-Dichaete* & *Tc-opa* expression patterns.
Fig S5. Expression patterns of Tc-cad, Tc-Dichaete, and Tc-opa in relation to each other in Tribolium castaneum germband stage embryos.

(A-F). Double in situ hybridization for Tc-cad (blue) and Tc-Dichaete (brown) in embryos of increasing age from left (A) to right (F). (G-L). As for panels (A-F), but this time Tc-Dichaete DIG and Tc-cad FITC RNA probes were used instead of Tc-cad DIG and Tc-Dichaete FITC RNA probes such that the colours are reversed. Note the stripe of Tc-Dichaete expression that is observed anterior to the Tc-cad domain in some, but not all, embryos. (M-R). Double in situ hybridization for Tc-cad (blue) and Tc-opa (brown) in embryos of increasing age from left (M) to right (N). Panels (M'-R') show higher magnification images of the regions in M-R where Tc-cad and Tc-opa expression overlaps. These data suggest that as posterior germband cells move anteriorly relative to the posterior tip of the elongating embryo due to convergent extension cell movements, they experience a drop in Tc-cad expression levels as Tc-opa expression levels increase. (S-X). Double in situ hybridization for Tc-Dichaete (blue) and Tc-opa (brown) in embryos of increasing age from left (S) to right (X). Black arrows points to late Tc-opa segmental stripes that overlap strong segmentally-reiterated Tc-Dichaete expression domains that are limited to the medially positioned neuroectoderm. Colour-coded lines on the right-hand side of the embryos indicate our interpretations of the expression patterns in (A-X).
Fig. S6. Details of cad and opa expression in Drosophila are paralleled in Tribolium.

(A) At gastrulation, cad is transiently expressed in weak pair-rule stripes (white arrowheads). These stripes have previously been observed at the protein level during germband extension (Macdonald & Struhl 1986). (B) Weak pair-rule stripes of Tc-cad (blue arrowheads) are sometimes observed anterior to the broad posterior domain. The domain corresponding to the lower arrowhead in the left panel has been reported previously (Schulz & Tautz 1995). In both Drosophila and Tribolium, these pair-rule cad stripes are located in the posterior of even-numbered parasegments, overlapping with even-numbered wg stripes. (C) During germband extension, ventral opa expression transitions to a segmental pattern. opa stripes posteriorly abut each en stripe, but are excluded from the cell row anterior to each en stripe. (D) Tc-opa exhibits an equivalent pattern in the segmented germband, posteriorly abutting each Tc-en stripe (images from Fig. S10).
Fig. S7. Expression of Tc-prd relative to Tc-cad in Tribolium germband stage embryos.

(A–O) Double in situ hybridization for Tc-prd (blue) and Tc-cad (brown) in embryos of increasing age from youngest (A) to oldest (O). Colour-coded lines on the right-hand side of the embryos indicate our interpretations of the expression patterns in (A–O). Note how the primary pair-rule stripes of Tc-prd first appear and form within the anterior half of the posterior Tc-cad domain (see where blue lines overlap brown lines). In contrast, segmental stripes of Tc-prd expression resolve by splitting just anterior to the Tc-cad domain (see where blue lines lie anterior to the brown line).
Fig. S8. Expression of Tc-prd relative to Tc-Dichaete in Tribolium germband stage embryos.

(A-T) Double in situ hybridization for Tc-prd (blue) and Tc-Dichaete (brown) in embryos of increasing age from youngest (A) to oldest (T). Colour-coded lines on the right-hand side of the embryos indicate our interpretations of the expression patterns in (A-T). Note how the primary pair-rule stripes of Tc-prd first appear and form within the posterior-most Tc-Dichaete domain (see where blue lines overlap brown lines). In contrast, segmental stripes of Tc-prd expression resolve by splitting anterior to this domain (see where blue lines lie anterior to the brown line). While dissecting and cleaning the embryos we noted that Tc-prd expression remains on stronger and longer in the overlying amnion compared to the underlying ectoderm; this is particularly apparent in panels (K-M), where the Tc-prd stained amnion has been ripped away while cleaning the embryo of yolk to reveal ectoderm free from Tc-prd expression (asterisks). Amnion-related expression can be seen down the lateral margins of many of the embryos where some amnion cells survived dissection and cleaning.
Fig. S9. Expression of *Tc-run* relative to *Tc-Dichaete* in *Tribolium* germband stage embryos.

(A–O) Colour-coded lines on the right-hand side of the embryos indicate our interpretations of the expression patterns. Blue arrowheads mark the primary pair-rule stripes that have most recently resolved – or are in the process of resolving – to a segmental periodicity. In some younger embryos (A–H), more than two stripes are apparent due to differences in the timing and/or positioning of this process between the amnion and ectoderm cell layers. Note how *Tc-run* stripe splitting occurs anterior to the posterior-most *Tc-Dichaete* domain (as judged by brown line by side of embryo). Older embryos show additional domains of *Tc-run* expression in the head lobes (H–O) and neuroectoderm (J–O), which were used to help stage the embryos.
Fig. S10. Expression of Tc-opa relative to Tc-en, Tc-eve and Tc-odd in Tribolium castaneum germband stage embryos.

(A-E) Double in situ hybridization for Tc-en (blue) and Tc-opa (brown) in embryos of increasing age from left (A) to right (E). Note how the Tc-en stripes (solid black arrowheads in C, D) form within the Tc-opa domain, but in a stripe-shaped region that is already clearing of Tc-opa expression (empty black arrowheads in A, B, E). (F-J) As for (A-E), but this time double in situ hybridization for Tc-eve (blue) and Tc-opa (brown). (K-O) As for (A-E), but this time double in situ hybridization for Tc-odd (blue) and Tc-opa (brown). In (F-O) note how the segmental stripes of Tc-odd and Tc-eve (labeled a & b) resolve within the Tc-opa domain. In (F-O) blue arrowheads mark Tc-odd and Tc-eve segmental stripes that have most recently resolved, or are in the process of resolving.
Fig. S11. Similar *Tc-opa* RNAi segmentation phenotypes are observed in distinct RNAi experiments, albeit at differing frequencies.

(A) Wildtype larval cuticles. (B) Representative cuticles from 3’ parental RNAi (pRNAi), 5’ pRNAi, 3’ eRNAi and 5’ eRNAi experiments, displaying similar local segment fusion phenotypes. The frequency of these phenotypes was between 15% and 37% across the four different RNAi experiments. The relative frequency of cuticles exhibiting local segment fusions, and the number of fused segments per embryo, was higher in eRNAi compared to pRNAi (see Supplementary Tables 1-3 and text for further details). (C) Representative cuticles from 3’ pRNAi, 3’ eRNAi and 5’ eRNAi, experiments displaying similar strong segmentation phenotypes. Less then 1% of cuticles exhibited these phenotypes in 3’ pRNAi, and none were observed in 5’ pRNAi, whereas their number and frequency was higher following 3’ & 5’ eRNAi (11-15%). Three representative cuticles are shown for each eRNAi experiment to illustrate the consistent ‘pair-rule-like’ appearance of these phenotypic cuticles; i.e. T1 & T2 legs fused, mandibular and labial appendages often lost, and only 4 abdominal segments obvious.
Fig S12. Similar Tc-opa RNAi appendage and head phenotypes are observed in distinct RNAi experiments, with associated defects found in Tc-opa pRNAi germband embryos.

(A) Wildtype larval cuticles. (B-D) The relative frequency of twisted antenna(e), abnormal leg(s) and T2 leg bifurcation(s) larval phenotypes observed in the 3’ pRNAi, 5’ pRNAi, 3’ eRNAi and 5’ eRNAi experiments, compared with sham injection controls. NB. An equivalent graph for head phenotypes is shown in Fig. 7. Refer to Tables S1-3 for exact details of the relative frequency of these phenotypes across the RNAi experiments and their controls. (E) Representative cuticles from each RNAi experiment exhibiting either one or two antennae that are abnormally twisted backwards (white arrowheads). (F) Representative cuticles from each RNAi experiment showing abnormalities in leg development (white arrowheads); note that these deformities included one or more of the following: twisted leg, short leg (absorbed into body wall), fused leg segments, bifurcated leg. (G) Representative cuticles from each RNAi experiment exhibiting asymmetric T2 leg bifurcations (white arrowheads); note that the proximodistal position of these bifurcations varied (from femur to claw). This phenotype represents a common subclass within the ‘abnormal leg(s)’ class of phenotype. (H) Representative cuticles from each RNAi experiment with weak head phenotypes, defined as a reduced head capsule (Hc) and/or labrum, judged in relation to the size of the prothoracic segment (T1). (I) Representative cuticles from each RNAi experiment with strong head phenotypes, defined as a complete absence of the head capsule (Hc), labrum and antennae, with only gnathal appendages (Gn) remaining. (J-O) Germband stage embryos from Tc-opa pRNAi females (K, M, O) compared to stage-matched embryos (using Tc-wg expression; red) from sham-injected control females (J, L, N). Tc-opa pRNAi germband embryos exhibit abnormalities that correlate with the antennal and head larval cuticle phenotypes: (i) Reduced (K) or missing (M, O) head lobes, likely reflecting the weak (H) and strong (I) head cuticle phenotypes respectively. (ii) Missing antennal Tc-opa (black arrowhead in J) & Tc-wg (black arrow in J) expression domains (compare J to K), possibly linked to the twisted antenna(e) phenotype (E). (NB. We suspect that disruption of the early blastoderm wedge shape domain shown in Fig. 8, which covers the future antennal segment, is linked to the broad head phenotypes (H, I), whereas disruption of the later domains of Tc-opa expression within the antennal segment is responsible for twisted antenna(e)). (iii) Reduced Tc-opa expression at the base of, and/or surrounding, developing appendages (black arrowheads in N; compare to the stage-matched Tc-opa RNAi embryo in O). Note that Tc-opa expression within and/or surrounding some gnathal appendages (i.e. mandibles; Mn & maxillae; Mx in N) is much stronger than that seen in/around leg appendages, and remains relatively strong in RNAi embryos (O), perhaps explaining why gnathal appendages were refractory to our Tc-opa RNAi. (iv) A patch of ectopic Tc-wg expression on the left side of the T2 segment (white arrowhead in O), is likely associated with the T2 leg bifurcations we observe in cuticles (G); note that the knockdown of Tc-opa seems quite efficient in the T2 segment (O), perhaps resulting in the derepression of Tc-wg (see Discussion).
Fig. S13. The Tc-opa RNAi blastoderm phenotype.

(A) The percentage of eggs that had reached the germ band stage in early 48-hour (30°C) egg collections taken from 3’ and 5’ Tc-opa parental RNAi (pRNAi) females and their parallel control (buffer) injected females. Both 3’ and 5’ Tc-opa pRNAi results in a drop in the percentage of germ band stage embryos relative to controls, however this reduction is much more dramatic with 5’ Tc-opa pRNAi.

(B) A random sample of 50 germ band-less eggs was taken from the same 5’ Tc-opa pRNAi egg collection as shown in (A) and stained with DAPI. Despite being up to 48-hours old, only one egg (2%) had formed a blastoderm; this egg is shown in panel (B’’’). The majority of eggs (68%) exhibited cleavage nuclei within the yolk, suggesting that in most of these eggs embryogenesis had started, but development had stalled prior to blastoderm stage (one of these eggs is shown in B’). The remaining 30% of eggs showed no sign of cleavage nuclei (although a polar body nuclei was clearly present in some cases; example shown in B’). However, it cannot be ruled out that some of these eggs possessed early cleavage nuclei undetected deeper within the yolk.
Fig. S14. Increased frequency of cuticle ball and cuticle fragment phenotypes following *Tc-opa* RNAi. (A) The percentage of cuticles scored as ‘cuticle balls’ and/or ‘cuticle fragments’ following pRNAi or eRNAi and associated parallel injection controls. Cuticle balls/fragments were observed in higher numbers in our second 5’ pRNAi experiment (see discussion associated with Table SI), and in 3’ and 5’ eRNAi experiments, when compared to injection controls. (B-C) Examples of eRNAi eggs containing cuticle balls and/or cuticle fragments arranged in two highly speculative phenotypic series. Note that in each of the eight images a fully developed hindgut (Hg) is present, suggesting that this aspect of development proceeded as normal. The speculative phenotypic series in row (B) begins on the left with a cuticle that would have been classified as a strong head phenotype (note the lone pair of maxillae and almost complete abdomen) had its thoracic and/or anterior abdominal segments (?) not collapsed and shriveled up into a bristle lined cylinder. Numerous cuticles assigned to this phenotypic class were bristle-lined cylinder-shaped cuticles (with an absence of other discernible features); increasingly severe examples are shown along row (B). In contrast, the speculative phenotypic series in row (C) begins on the left with a large cuticle ball that could be interpreted as an extreme segmentation phenotype, with gnathal appendages perhaps present but indecipherable, evidence of only extremely short legs and less than 4 clear abdominal segments. Numerous cuticles assigned to this phenotypic class were smaller cuticle balls, attached to – or alongside – a fully developed hindgut, whereas other eggs exhibited cuticles that appeared to have broken up, with some recognizable structures remaining (e.g. a fully developed leg); examples of these are arranged in order of increasing severity along row (C). These cuticles are almost impossible to interpret, since no two are entirely alike, and examples are also observed following embryonic control injections. However, given their increased relative frequency in 3’ and 5’ *Tc-opa* eRNAi compared to controls, and their observation in a 5’ pRNAi experiment (i.e. arguing against injection artifacts being solely responsible), it is possible that at least some of these cuticles are the direct, or indirect, result of strong *Tc-opa* RNAi knockdowns, and represent extreme head and/or segmentation phenotypes. This may explain why in the *Tc-opa* eRNAi experiments only 10-15% of eggs exhibit clear and interpretable pair-rule-like phenotypes.
Supplementary Table 1

The percentage of cuticles that exhibited each class of egg or cuticle phenotype in each of the parental RNAi experiments and their corresponding parallel injection controls. Table includes total number of eggs or cuticles scored.

| Phenotypic cuticle (%) | 3' RNAi | Cont. | 5' RNAi | 3' Cont. | 5' Cont. | 300 | 300 | 284 |
|------------------------|---------|-------|---------|----------|----------|-----|-----|-----|
| Empty eggs (%)         | 26.6    | 16.1  | 94.1    | 71.7     | 22.7     | 85.7| 19.4|
| Wildtype cuticles (%)  | 37.9    | 81.9  | 1.0     | 23.3     | 27.3     | 2.0 | 76.1|
| Phenotypic cuticles (%)| 35.5    | 2.0   | 4.6     | 0.2      | 50.0     | 12.3| 4.6 |
| Not scorable (%)       | -       | -     | 0.3     | 4.8      | -        | -   | -   |

| Wildtype cuticles (%)  | 51.7    | 97.6  | 18.2    | 99.1     | 35.3     | 14.0| 94.3|
| Phenotypic cuticles (%)| 48.3    | 2.4   | 81.8    | 0.9      | 64.7     | 86.0| 5.7 |
| Antennae abnormal (lost, reduced, twisted, bifurcated) (%) | 29.0 | 0.0 | 77.3 | 0.9 | 44.8 | 67.4 | 0.0 |
| Antennae twisted backwards (%) | 18.4 | 0.0 | 40.9 | 0.0 | 25.0 | 37.2 | 0.0 |
| Leg(s) abnormal (twisted, bifurcated, short, fused segments) (%) | 16.0 | 0.6 | 31.8 | 0.0 | 30.6 | 30.2 | 0.9 |
| At least one T2 leg bifurcated (branching position varies) (%) | 10.6 | 0.0 | 13.6 | 0.0 | 18.5 | 14.0 | 0.0 |
| Anterior head (head capsule and/or labrum) reduced (%) | 16.0 | 0.0 | 45.5 | 0.0 | 22.0 | 34.9 | 0.4 |
| Weak (head capsule and/or labrum present, but reduced) (%) | 14.2 | 0.0 | 27.3 | 0.0 | 15.5 | 14.0 | 0.0 |
| Strong (missing, usually only gnathal appendages remain) (%) | 1.9 | 0.0 | 18.2 | 0.0 | 6.5 | 20.9 | 0.4 |
| Total segment fusion phenotypes (%) | 15.3 | 0.0 | 27.3 | 0.0 | 21.6 | 11.6 | 0.9 |
| Total cuticles with local segment fusions (%) | 14.6 | 0.0 | 27.3 | 0.0 | 21.1 | 11.6 | 0.9 |
| Fusion of T3/A1 only (%) | 11.1 | 0.0 | 18.2 | 0.0 | 16.4 | 7.0 | 0.0 |
| Total cuticles with T3/A1 fusions (%) | 13.2 | 0.0 | 22.7 | 0.0 | 17.7 | 9.3 | 0.0 |
| Local segment fusions in segment(s) other than T3/A1 (%) | 3.5 | 0.0 | 9.1 | 0.0 | 4.7 | 4.7 | 0.9 |
| Strong ‘pair-rule’ phenotype (all segments affected) (%) | 0.7 | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 0.0 |
| Cuticle ball and/or cuticle fragments (%) | 1.9 | 0.6 | 0.0 | 0.0 | 0.9 | 18.6 | 1.3 |
| Miscellaneous abnormalities | 2.1 | 1.3 | 9.1 | 0.0 | 4.3 | 7.0 | 4.4 |

In the first round of pRNAi experiments 3' and 5' dsRNA was injected into adult females on different days, each time alongside parallel injection controls, such that there is a control group associated with each dsRNA fragment. The same population (box) of animals was used, and subsequent egg collections were made at the same times in relation to the day of injection. In the second round of pRNAi experiments, 3' and 5' dsRNA was injected on the same day, alongside one set of injection controls. In the first 5' pRNAi experiment, cuticle preparations were made before all eggs would have had the opportunity to secrete cuticles. It is notable that the control eggs possessed a significant number of embryos that were in the process of secreting cuticle (23/480), and therefore “Not scorable” as wildtype or phenotypic cuticles (fifth line of table). In contrast, 5' pRNAi eggs possessed very few developing embryos (1/392), consistent with the higher level of empty eggs in this experiment. The second round of pRNAi experiments was therefore carried out partly to gain a more accurate measure of the frequency of empty eggs, but also acted as an experimental repeat. In order to gain a more accurate comparison between the frequencies of empty eggs in pRNAi...
vs. eRNAi experiments, in the second pRNAi experiments eggs from injected females were lightly bleached and lined up on slides, as they would be for embryonic injection.

We note that the second set of 3’ and 5’ pRNAi experiments appear to have resulted in stronger knockdowns. Importantly, the same classes of phenotype were observed across all pRNAi experiments. However, the frequency of phenotypes, and/or the frequency of stronger phenotypes relative to weaker ones, was generally higher in the second round of pRNAi experiments. Of particular note is the higher number of cuticle balls/fragments observed in the second 5’ pRNAi experiment. There are a number of potential explanations for this, none mutually exclusive: (i) 5’ pRNAi eggs (i.e. stronger knockdowns) were more sensitive to the mechanical manipulation associated with lining eggs up on slides; this might also explain the high number of cuticle balls/fragments seen in eRNAi experiments. (ii) Cuticle ball/fragment phenotypes represent a stronger knockdown than strong head phenotypes (see Fig. S14). This is supported by the observation that although the frequency of head phenotypes was lower overall in the second 5’ pRNAi experiment, there was a higher proportion of strong head phenotypes (60% vs. 40%). (iii) The lower number of cuticles obtained and scored for the 5’ pRNAi experiments (e.g. 43 compared to 232 for 3’ pRNAi), means that the data are more sensitive to random variations.

Supplementary Table 2

The percentage of cuticles that exhibited each class of egg or cuticle phenotype in each of the embryonic RNAi experiments and their corresponding parallel injection controls. Table includes total number of eggs or cuticles scored.

| Embryonic RNAi | 3’ | 5’ | Controls |
|---------------|----|----|---------|
| **Eggs examined (n)** | 198 | 252 | 198 |
| Empty eggs (%) | 40.4 | 46.4 | 27.8 |
| Wildtype cuticles (%) | 3.5 | 7.5 | 55.1 |
| Phenotypic cuticles (%) | 56.1 | 46.0 | 17.2 |
| **Cuticles scored (n)** | 118 | 135 | 143 |
| Wildtype cuticles (%) | 5.9 | 14.1 | 76.2 |
| Phenotypic cuticles (%) | 94.1 | 85.9 | 23.8 |
| Antennae abnormal (lost, reduced, twisted, bifurcated) (%) | 32.2 | 34.1 | 2.1 |
| Antennae twisted backwards (%) | 9.3 | 8.1 | 0.0 |
| Leg(s) abnormal (twisted, bifurcated, short, fused segments) (%) | 56.8 | 48.9 | 1.4 |
| At least one T2 leg bifurcated (branching position varies) (%) | 15.3 | 11.1 | 0.0 |
| Anterior head (head capsule and/or labrum) reduced (%) | 31.4 | 32.6 | 1.4 |
| Weak (head capsule and/or labrum present, but reduced) (%) | 17.8 | 18.5 | 0.0 |
| Strong (missing, usually only gnathal appendages remain) (%) | 13.6 | 14.1 | 1.4 |
| Total segment fusion phenotypes (%) | 48.3 | 45.2 | 2.8 |
| Total cuticles with local segment fusions (%) | 37.3 | 30.4 | 2.8 |
| Fusion of T3/Al only (%) | 4.2 | 5.9 | 0.0 |
| Total cuticles with T3/Al fusions (%) | 19.5 | 20.7 | 0.0 |
| Local segment fusions in segment(s) other than T3/Al (%) | 33.1 | 24.4 | 2.8 |
| Strong ‘pair-rule’ phenotype (all segments affected) (%) | 11.0 | 14.8 | 0.0 |
| Cuticle ball and/or cuticle fragments (%) | 27.1 | 28.9 | 12.6 |
| Miscellaneous abnormalities | 4.2 | 7.4 | 8.4 |
Supplementary Table 3

The percentage of cuticles that exhibited each class of egg or cuticle phenotype in each of the parental and embryonic RNAi experiments. Table includes total number of eggs or cuticles scored.

| Phenotype | Parental RNAi | Embryonic RNAi |
|-----------|---------------|----------------|
|           | Experiment 1  | Experiment 2   |
|           | 3' 5'         | 3' 5'          |
|           | 3' 5'         | 3' 5'          |
| Eggs examined (n) | 578 392 | 300 300 | 198 252 |
| Empty eggs (%) | 26.6 94.1 | 22.7 85.7 | 40.4 46.4 |
| Wildtype cuticles (%) | 37.9 1.0 | 27.3 2.0 | 3.5 7.5 |
| Phenotypic cuticles (%) | 35.5 4.6 | 50.0 12.3 | 56.1 46.0 |
| Not scorable (%) | - 0.3 | - - | - - |
| Cuticles scored (n) | 424 22 | 232 43 | 118 135 |
| Wildtype cuticles (%) | 51.7 18.2 | 35.3 14.0 | 5.9 14.1 |
| Phenotypic cuticles (%) | 48.3 81.8 | 64.7 86.0 | 94.1 85.9 |
| Antennae abnormal (lost, reduced, twisted, bifurcated) (%) | 29.0 77.3 | 44.8 67.4 | 32.2 34.1 |
| Antennae twisted backwards (%) | 18.4 40.9 | 25.0 37.2 | 9.3 8.1 |
| Leg(s) abnormal (twisted, bifurcated, short, fused segments) (%) | 16.0 31.8 | 30.6 30.2 | 56.8 48.9 |
| At least one T2 leg bifurcated (branching position varies) (%) | 10.6 13.6 | 18.5 14.0 | 15.3 11.1 |
| Anterior head (head capsule and/or labrum) reduced (%) | 16.0 45.5 | 22.0 34.9 | 31.4 32.6 |
| Weak (head capsule and/or labrum present, but reduced) (%) | 14.2 27.3 | 15.5 14.0 | 17.8 18.5 |
| Strong (missing, usually only gnathal appendages remain) (%) | 1.9 18.2 | 6.5 20.9 | 13.6 14.1 |
| Total segment fusion phenotypes (%) | 15.3 27.3 | 21.6 11.6 | 48.3 45.2 |
| Total cuticles with local segment fusions (%) | 14.6 27.3 | 21.1 11.6 | 37.3 30.4 |
| Fusion of T3/A1 only (%) | 11.1 18.2 | 16.4 7.0 | 4.2 5.9 |
| Total cuticles with T3/A1 fusions (%) | 13.2 22.7 | 17.7 9.3 | 19.5 20.7 |
| Local segment fusions in segment(s) other than T3/A1 (%) | 3.5 9.1 | 4.7 4.7 | 33.1 24.4 |
| Strong 'pair-rule' phenotype (all segments affected) (%) | 0.7 0.0 | 0.4 0.0 | 11.0 14.8 |
| Cuticle ball and/or cuticle fragments (%) | 1.9 0.0 | 0.9 18.6 | 27.1 28.9 |
| Miscellaneous abnormalities | 2.1 9.1 | 4.3 7.0 | 4.2 7.4 |