A damped oscillator imposes temporal order on posterior gap gene expression in *Drosophila*

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August 5, 2016

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Subject categories: Quantitative Biology & Dynamical Systems, Network Biology, Computational Biology

Keywords: Regulatory Network / Biological Oscillations / Pattern Formation / Evolutionary Developmental Biology / Segment Determination

Running Title: A damped oscillator in *Drosophila* segmentation

character count (including spaces): 60.990

Abstract

Insects determine their body segments in two different ways. Short-germband insects, such as the flour beetle *Tribolium castaneum*, use a molecular clock to establish segments sequentially. In contrast, long-germband insects, such as the vinegar fly *Drosophila melanogaster*, determine all segments simultaneously through a hierarchical cascade of gene regulation. Gap genes constitute the first layer of the *Drosophila* segmentation gene hierarchy, downstream of maternal gradients. We use data driven modelling and phase space analysis to show that shifting gap domains in the posterior half of the *Drosophila* embryo are an emergent property of a robust damped oscillator mechanism. The rate at which gap domains shift is determined by the level of maternal Caudal (Cad), which also regulates the frequency of the *Tribolium* molecular clock. Our evidence indicates that the regulatory dynamics underlying long- and short-germband segmentation are much more similar than previously thought. This similarity may help explain why long-germband segmentation evolved convergently multiple times during the radiation of the holometabolan insects.

Introduction

The segmented body plan of insects is established by two very different modes of development (Sander (1976); Davis and Patel (2002); Rosenberg *et al* (2009); Lynch *et al* (2012)). *Long-germband insects*, such as the vinegar fly *Drosophila melanogaster*, determine almost all of their segments simultaneously during the blastoderm stage, before the onset of gastrulation (Akam (1987); Jaeger (2011)). The segmental pattern is set up by subdivision of the embryo into different territories, prior to any growth or tissue rearrangements. *Short-germband insects*, such as the flour beetle *Tribolium castaneum*, determine most of their segments after gastrulation, with segments being patterned sequentially from a posterior *segment addition zone*. This process involves tissue growth or rearrangements as well as dynamic travelling waves of gene expression driven by a molecular clock mechanism (Sarrazin *et al* (2012); El-Sherif *et al* (2012, 2014); Nakamoto *et al* (2015)). The available evidence strongly suggests that the short-germband mode of segment determination is ancestral, while the long-germband mode is evolutionarily derived (Sander (1976); Davis and Patel (2002); Liu and Kaufman (2005)).

The long-germband mode of segmentation has evolved convergently multiple times (Davis and Patel (2002); Liu and Kaufman (2005); Peel (2008)). It can be found scattered over all four major holometabolous insect orders (Hymenoptera, Coleoptera, Lepidoptera, and Diptera), even though the ancestors of each of these clades probably patterned through a short-germband mode. Furthermore, there has been at least one reversion from long- to short-germband segmentation in polyembryonic wasps (Sucena *et al* (2014)). This suggests that despite the apparent differences between the two segmentation modes, it seems relatively easy to evolve one from the other. Why this is so, and how the transition is achieved, remains unknown.

In this paper, we show that the dynamics of long- and short-germband segmentation are much more similar than previously thought. Specifically, we demonstrate that shifting patterns of segmentation gene expression in the posterior of the *D. melanogaster* embryo are driven by a damped oscillator mechanism, reminiscent of the clock-like dynamics underlying short-germband segmentation. We achieve this through analysis of a quantitative, data-driven gene circuit model of the gap network in *D. melanogaster*. The gap gene system constitutes the top-most hierarchical layer of the segmentation gene cascade (Jaeger (2011)). Gap genes *hunchback (hb)*, *Krüppel (Kr)*, *giant (gt)*, and *knirps (kni)* are activated through gradients formed by the products of maternal co-ordinate genes *bicoid (bcd)* and *caudal (cad)*. They become expressed during the blastoderm stage in broad overlapping domains along the antero-posterior (A–P) axis of the embryo (Fig 1A). Gap genes are responsible for regulating periodic pair-rule gene expression, through combinatorial repression of individual stripes. Pair-rule genes, in turn, establish the precise pre-pattern of the segment-polarity genes, whose activities govern the morphological formation of body segments later in development, after gastrulation has occurred.

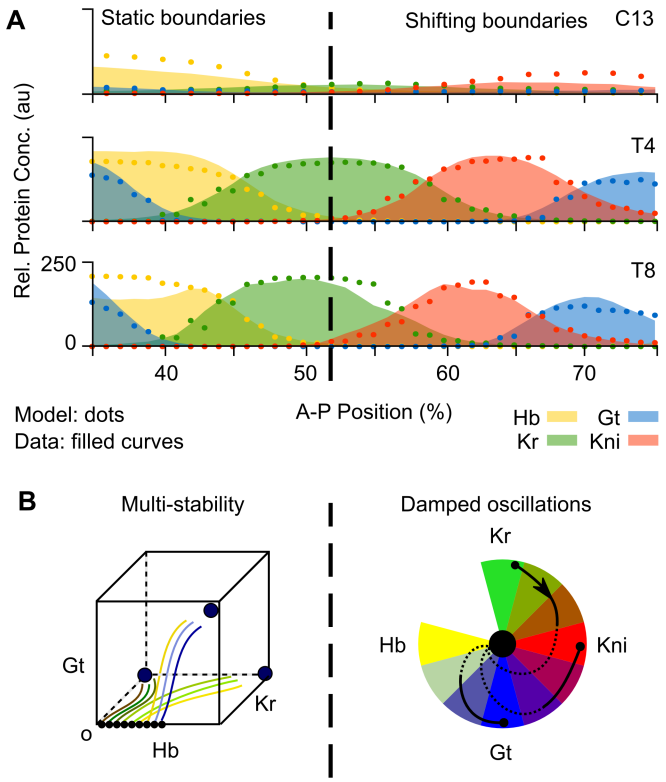

Figure 1: **Dynamics of gap gene pattern formation in *D. melanogaster*. (A)** Gap protein expression data (coloured areas) and model output (dots), shown at cleavage cycles C13 and C14A (time classes T4 and T8). Hb in yellow, Kr in green, Kni in red, Gt in blue (see key). X-axes: % A–P position (where 0% is the anterior pole); Y-axes: relative protein concentration (in arbitrary units). Dashed vertical line indicates bifurcation boundary between static and shifting gap domain borders (at 52% A–P position). **(B)** Dynamic regimes governing gap gene expression in the anterior versus the posterior of the embryo. Static anterior boundaries are set by attractors in a multistable regime, as shown in the stylized phase portrait on the left; shifting posterior boundaries are driven by a damped oscillator implemented by a monostable spiral sink (right). Colour wheel with black trajectories represents ordered dynamics of gap gene expression driven by the damped oscillator (see text for details).

In contrast to earlier work (Jaeger *et al* (2004b,a); Manu *et al* (2009b,a); Gursky *et al* (2011)), we use a non-autonomous dynamical system to model gap gene regulation (Ashyraliyev *et al* (2009); Verd *et al* (2014)). This model formulation explicitly considers the time-dependence of regulatory inputs by maternal gradients, which change and decay on the same timescale as gap gene expression (Surkova *et al* (2008)). This renders our non-autonomous gene circuits more accurate and realistic than previous autonomous models (Verd *et al* (2016)).

Dynamical systems theory provides powerful tools for the analysis of complex regulatory mechanisms (Strogatz (2014)). Geometrical analysis of phase space can be used to identify and characterise steady states and their associated basins of attraction, which determine the *phase portrait* of a system. The phase portrait defines the *dynamic regimes* that govern gene expression. Dynamic regimes determine the flow of the system, *i. e.* the shape of its trajectories, which specifies how regulator concentrations can change over time. This type of geometrical analysis was successfully used to characterise the robust (canalised) patterning dynamics of an autonomous gap gene circuit (Manu *et al* (2009b,a); Vakulenko *et al* (2009); Gursky *et al* (2011)). Phase space of non-autonomous models is special in that it is time-variable: the number, nature, and position of steady states can change from one time point to the next. Bifurcations—the creation or annihilation of steady states—may occur over time as the flow changes, and system trajectories may cross from one basin of attraction to another. We use instantaneous phase portraits (Collier *et al* (1996); Verd

et al (2014)) to capture the time-variable geometry of phase space and its influence on system trajectories in a non-autonomous gap gene circuit. A detailed and systematic account of this analysis is given elsewhere (Verd *et al* (2016)). Here, we will focus on the regulatory mechanism underlying patterning dynamics in the posterior of the embryo.

In agreement with earlier work (Manu *et al* (2009a)), analysis of a non-autonomous gap gene circuit reveals different types of dynamics in the anterior versus the posterior of the *D. melanogaster* embryo (Fig 1B) (Verd *et al* (2016)). In the anterior, where boundary positions remain stationary over time, gap gene expression dynamics are governed by a multistable dynamical regime in both autonomous and non-autonomous models (Manu *et al* (2009a); Verd *et al* (2016)). In contrast, dynamics in the posterior region differ between the two models. Posterior gap domains shift anteriorly over time (Jaeger *et al* (2004b); Surkova *et al* (2008)). In autonomous models, these shifts are driven by a feature of phase space called a transient unstable manifold (Manu *et al* (2009a)). In non-autonomous models, they are governed by a monostable spiral sink, which shapes the geometry of transient trajectories (Fig 1B). The presence of a spiral sink implies a damped oscillator mechanism driving gap domain shifts (Strogatz (2014)). In this report, we present a detailed analysis of this oscillator mechanism and discuss its implications for pattern formation and the evolution of the gap gene system. Our results suggest that long-germband and short-germband modes of segmentation both involve oscillatory regimes in the posterior region of the embryo, that generate posterior to anterior waves of gene expression. These unexpected similarities suggest an explanation for the high frequency of convergent transitions between the two modes of segment determination during holometabolan insect evolution.

Results and Discussion

Gap domain shifts are an emergent property of a damped oscillator

Gap domain boundaries posterior to 52% A–P position shift anteriorly over time (Fig. 1A) (Jaeger *et al* (2004b); Surkova *et al* (2008)). These domain shifts cannot be explained by nuclear movements (Keränen *et al* (2006)), nor do they require diffusion or transport of gap gene products between nuclei (Jaeger *et al* (2004b); Manu *et al* (2009b,a); Verd *et al* (2016)). Instead, gap domain shifts are kinematic, caused by an ordered temporal succession of gene expression in each nucleus, which produces apparent wave-like movements in space (Jaeger *et al* (2004b); Manu *et al* (2009a)). This is illustrated in Fig. 2A. Each nucleus starts with a different initial concentration of maternal Hb, which leads to the expression of different zygotic gap genes: *Kr* in the central region of the embryo, or *kni* further posterior. Nuclei then proceed through a stereotypical temporal progression where *Kr* expression is followed by *kni* (*e. g.* nucleus at 59%), *kni* by *gt* (nucleus at 69%) and, finally, *gt* by *hb* (nuclei posterior of 75%; not shown). No nucleus goes through the expression of all four trunk gap genes over the course of the blastoderm stage and each nucleus goes through a different partial sequence within this progression, which is determined by its starting state. This coordinated dynamic behaviour is what we need to explain in order to understand the regulatory mechanism underlying gap domain shifts.

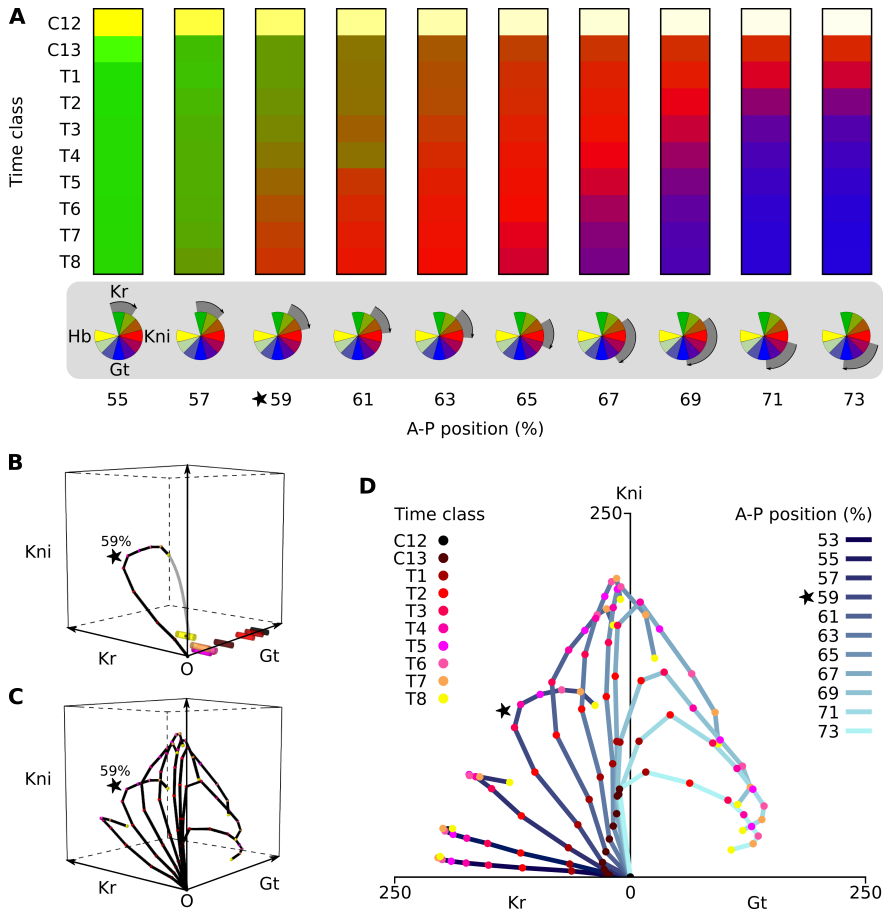

Figure 2: **A damped oscillator governs posterior gap gene patterning in *D. melanogaster*.** **(A)** Kinematic gap domain shifts and temporal order of gene expression. Temporal dynamics of gap gene expression in posterior nuclei between 55% and 73% A–P position shown as columns. Developmental time proceeds down the Y-axis, covering cleavage cycles C13 and C14A (time classes T1–8). C12 indicates initial conditions: maternally provided Hb concentrations indicated by yellow shading at the top of each column. Kr concentration is shown in shades of green, Kni in red, and Gt in blue. The kinematic anterior shift of the Kni domain (in red) is clearly visible. Colour-wheels (at the bottom of the columns) represent ordered succession of gap gene gene expression imposed by the damped oscillator mechanism. Black arrows indicate the section (phase range) of the clock period that the oscillator traverses in each nucleus over the duration of the blastoderm stage. The position of each arrow depends on the initial Hb concentration in that nucleus. **(B)** Three-dimensional projection of the time-variable phase portrait for the nucleus at 59%A–P position. Axes represent Kr, Kni, and Gt protein concentrations. Spiral sinks are represented by cylinders, colour-coded to show the associated developmental time point (see key). The trajectory of the system during C13 and C14A is shown in black, coloured points marking its progress through time. Asymptotic convergence of the trajectory (after the blastoderm stage has ended) is shown in grey. **(C)** Trajectories for nuclei at odd positions, between 57 and 69%A–P position. Projection, axes, and time points as in B). **(D)** Trajectories for the nuclei between 57 and 73%A–P position are represented unfolded onto the Kr-Kni and Gt-Kni planes. This is possible because there are at most two gap genes expressed in the same nucleus at the same time point, and hence trajectories localise onto these planes. A–P position of nuclei is given by the shade of blue of the trajectory: lighter coloured trajectories correspond to more posterior nuclei (see key). Time points as in (B). The star marks the nucleus at 59% A–P position. See Materials and Methods for time classes, and main text for further details.

We carried out a systematic characterisation of dynamic regimes in a non-autonomous gap gene circuit

(Verd *et al* (2016)). This analysis reveals that phase portraits of nuclei posterior to 52% A–P position are monostable throughout the blastoderm stage (see, for example, Fig. 2B). Given enough time, all trajectories would approach the only attractor present, which at T8 is located at high *hb* levels (Fig. 2B, yellow cylinder). Due to the non-autonomy of the system, this attractor moves across phase space over developmental time. However, this movement is not the most important factor determining the shape of trajectories. Due to the limited duration of the blastoderm stage, the system always remains far from steady state, and posterior gap gene expression dynamics are shaped by the geometry of transient trajectories, relatively independently of the precise position of the attractor. Because the moving attractor positions of all posterior nuclei are similar to those shown for the nucleus at 59% A–P (Fig. 2B), we are able to plot the trajectories of the different nuclei onto the same projection of phase space (Fig. 2C and D). It is evident from these plots that the observed ordered succession of gap gene expression is caused by the rotational (spiral-shaped) geometry of the trajectories. Posterior nuclei cycle through build-up of Kr, then Kni, then Gt protein, with their initial conditions determining where in this sequence they begin. The combination of the inherent temporal order of the trajectories with the spatial order of the various starting conditions produces the kinematic domain shifts shown in Fig. 2A.

Eigenvalue analysis reveals that the monostable steady state in posterior nuclei is a special type of point attractor: a spiral sink, or focus (Strogatz (2014); Verd *et al* (2016)). Trajectories do not approach a sink in a straight line, but spiral inward instead. This contributes to the curved rotational geometry of the trajectories shown in Fig. 2B–D, which are centred around the region of phase space surrounding the sink. From the theory of dynamical systems, we know that spiral sinks are the hallmark of damped oscillations (Strogatz (2014)). Given that spiral sinks are the only steady states present in the monostable phase portraits of posterior nuclei, we conclude that posterior gap gene expression dynamics in *D. melanogaster* are driven by a damped oscillator mechanism in our model. This damped oscillator mechanism imposes the observed temporal order of gap gene expression (Fig. 2A). Temporal order is a natural consequence of oscillatory dynamics. One well-known example for this is the stereotypical succession of cyclin gene expression driven by the cell cycle oscillator (*e. g.* Murray and Kirschner (1989); Novak *et al* (2010)).

Temporal order through damped oscillations provides a much more straightforward and intuitive explanation of gap domain shifts than the unstable manifold found in autonomous gap gene circuits (Manu *et al* (2009a); Vakulenko *et al* (2009); Gursky *et al* (2011)). In this sense, our analysis constitutes an important conceptual advance over previous characterisations. Yet, the proposed oscillatory mechanism is also counterintuitive in its own way. It never produces any repeating cyclical behaviour, such as the periodic waves of gene expression involved in short-germband segmentation in insects (Sarrazin *et al* (2012); El-Sherif *et al* (2012, 2014)) and other arthropods (Chipman *et al* (2004); Brena and Akam (2013)), or vertebrate somitogenesis (Palmeirim *et al* (1997); Oates *et al* (2012)). Still, it fully satisfies the definition of an oscillator: each nucleus runs through a different range of phases within a given time range (see color-wheel diagrams in Figure 2A), like clocks that never complete the hour. Arranged properly across space, such shifted partial phase oscillations create the observed kinematic waves of gene expression. In this sense, shifting gap domains in the *D. melangoaster* blastoderm and travelling waves of gene expression in short-germband embryos are driven by equivalent dynamics: they are both an emergent property of an underlying oscillatory regulatory mechanism.

Canalising properties of the gap gene damped oscillator

Domain shifts are not strictly necessary for subdividing an embryo into gene expression territories. Wolpert's French Flag paradigm for positional information, for example, works without any dynamic patterning downstream of the morphogen gradient (Wolpert (1968, 1969)). This raises the question of why such shifts occur and what, if anything, they contribute to pattern formation. One suggestion is that feedback-driven shifts lead to more robust patterning than a strictly feed-forward regulatory mechanism such as the French Flag (Jaeger and Reinitz (2006); Jaeger *et al* (2008)). This is supported by the fact that the unstable manifold in autonomous circuits Manu *et al* (2009a) has canalising properties: as time progresses, it attracts trajectories coming from different initial conditions into an increasingly small and localised sub-volume of phase space. This desensitizes the system to variation in maternal gradient concentrations (Manu *et al* (2009b)). Based

on these insights, we asked whether our damped oscillator mechanism exhibits similar canalising behaviour.

A closer examination of the spiral trajectories in Fig. 2C reveals that they are largely confined to two specific sub-planes in phase space. Specifically, they tend to avoid regions of simultaneously high Gt and Kr, allowing us to "unfold" the three-dimensional volume of Kr-Kni-Gt space into two juxtaposed planes representing Kr-Kni and Kni-Gt concentrations (Fig. 2D). This projection highlights how trajectories spend variable amounts of time in the Kr-Kni plane before they transition onto the Kni-Gt plane.

In order to investigate this phenomenon, we performed a numerical experiment, shown in Fig. 3A and B. We chose a set of regularly distributed initial conditions for our model that lie within the Kr-Gt plane (Fig. 3A). We use this set of initial conditions to simulate the nucleus at 59% A–P position with a fixed level of Kni (Fig. 3B). These simulations illustrate how system trajectories converge to the Kr-Kni or Kni-Gt plane, avoiding regions of simultaneously high Kr and Gt concentrations. Convergence occurs rapidly and is already far advanced in early cleavage cycle 14A (Fig. 3B, time class T1). At later stages, convergence slows down but continues restricting trajectories to an increasingly small sub-volume of phase space (up to late cleavage cycle 14A, Fig. 3B, time class T8). This behaviour is robust with regard to varying levels of Kni (Fig. S1). It demonstrates that the sub-volume of phase space in which trajectories are found becomes restricted long before a steady state is reached. This spatial restriction of transient trajectories is qualitatively equivalent to the canalising behaviour of the unstable manifold found in autonomous gap gene circuits (Manu *et al* (2009a)).

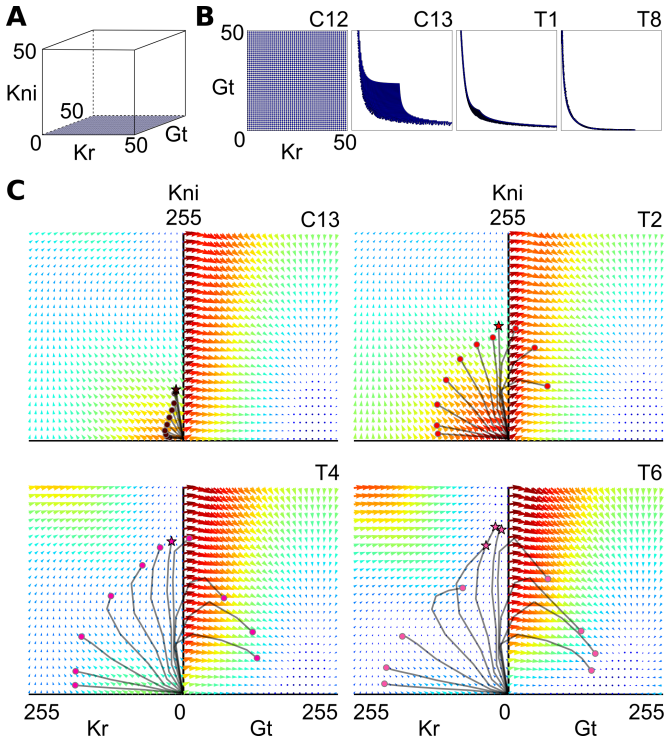

Figure 3: **Canalising properties and relaxation-like behaviour of the gap gene damped oscillator. (A, B)** Canalising properties: trajectories rapidly converge to planes in phase space. We simulate the non-autonomous diffusion-less circuit in the nucleus at 59% A–P position with Kni concentration fixed to zero and a set of initial conditions that are regularly distributed on the Kr-Gt plane. **A** Initial conditions shown in blue, embedded within the three-dimensional Kr-Kni-Gt space. **B** Two-dimensional projections of the Kr-Gt plane show converging system states as tiny blue dots at C12, C13, C14A-T1, and -T8. **(C)** Fast-slow dynamics in posterior nuclei are caused by relaxation-like behaviour. Unfolded, two-dimensional projections of the Kr-Kni and Kni-Gt planes are shown as in Fig. 2C at C13, C14A-T2, -T4, and -T6. Coloured arrows indicate magnitude and direction of flow: large red arrows represent strong flow, small blue arrows represent weak flow. Trajectories of posterior nuclei are superimposed on the flow (shown as black lines). Coloured circles at the end of trajectories indicate current state at each time point. Stars mark trajectories experiencing a positive Gt-component of the flow. See Materials and Methods for time classes, and main text for further details.

It is straightforward to interpret the exclusion of trajectories from regions of simultaneous high Kr and high Gt in terms of regulatory interactions. There is a strong double-negative (and hence positive) feedback loop between *gt* and *Kr*, which is crucial for the mutually exclusive expression patterns of these genes (Jaeger *et al* (2004a); Jaeger (2011); Crombach *et al* (2012)). In the context of our damped oscillator mechanism, this mutually exclusive feedback implies that the system must first transition from high Kr to high Kni/low Kr before it can initiate *gt* expression. This is exactly what we observe (Fig 2A), confirming that the damped oscillator in the posterior of the *D. melanogaster* embryo has canalising properties due to double-negative feedback between mutually exclusive gap genes.

Fast-slow dynamics through excitable relaxation-like oscillatory behaviour

How do spiral trajectories switch from one plane in phase space to another? Fig. 3C shows projections of the flow of our non-autonomous model onto the unfolded Kr-Kni and Kni-Gt planes, and maps trajectories and states of various posterior nuclei at different points in time onto this flow (see also Fig. S2). These plots reveal drastic differences in flow velocity (magnitude) in different regions of phase space at different points

in time. At early stages, close to the origin we observe a fast initial increase in Kr and Kni concentrations (Fig. 3C, C13 and T2, red arrows at low Kr and Kni values). Nuclei whose trajectories remain on the Kr-Kni plane then show a dramatic slow-down. They either continue to gradually increase levels of Kr, or exhibit slow build-up of Kni combined with consequent decrease of Kr (due to repression by Kni; Fig. 3C, T4 and T6). As trajectories in different nuclei approach the border between the Kr-Kni and Kni-Gt planes, the Gt-component of the flow on the Kr-Kni plane becomes positive (trajectories marked by stars in Fig. 3C). This "lifts" the trajectory out of the Kr-Kni and into the Kni-Gt plane. In the border zone, the flow in the direction of Gt is high throughout the blastoderm stage (Fig. 3C), ensuring that the switch between planes occurs rapidly. Nuclei then again enter a zone of slower dynamics with a gradual build-up of Gt, combined with consequent decrease of Kni (due to repression by Gt; Fig. 3C, T4 and T6).

Thus, the flow of our model combines relatively slow straight stretches within a plane of phase space with rapid turns at the border between planes. Similar alternating fast-slow dynamics have been observed in autonomous gap gene circuits (Vakulenko *et al* (2009)). They influence the width of gap domains (through relatively stable periods of expressing a specific gap gene), and the sharpness of domain boundaries (through abrupt changes in gene expression at borders between planes). Such fast-slow dynamics are characteristic of relaxation oscillations (Strogatz (2014)). A relaxation oscillator combines phases of gradual build-up in some of its state variables with rapid releases and changes of state. This results in an irregularly-shaped limit cycle attractor, which typically combines straight stretches of slow dynamics with rapid turns and changes of state, similar to what we observe for our damped gap gene oscillator. This suggests that the irregular geometries of spiralling transient trajectories represent relaxation-like oscillatory dynamics that govern the shape and the shift rate of posterior gap domains.

The fast-slow dynamics we observe are typical for excitable systems (also called excitable media). Such systems exhibit dynamics governed by a single attractor with transient dynamics that can send trajectories on long excursions through phase space (Strogatz (2014)). These conditions apply to both our non-autonomous system, as well as earlier autonomous models of the gap gene network (Manu *et al* (2009a); Vakulenko *et al* (2009)). Excitability is not only important for shifting gap domains, but occurs in a vast range of natural non-linear systems, including the Belousov–Zhabotinsky chemical reaction and fruiting body aggregation in slime molds (Winfree (1980); Murray (2001)). In this sense, gap domain shifts belong to a very common class of dynamic regulatory mechanisms, and insights from their study may apply in many other regulatory contexts.

Caudal regulates the velocity of gap domain shifts

In the short-germband beetle *T. castaneum*, an oscillator mechanism governs travelling waves of pair-rule gene expression (Sarrazin *et al* (2012); El-Sherif *et al* (2012)). The frequency of these repeating waves is positively correlated with the level of Cad in the posterior of the embryo (El-Sherif *et al* (2014)): the more Cad present, the faster the oscillations. In *D. melanogaster*, changing concentrations of maternal morphogens influence the rate and extent of posterior gap domain shifts (Wotton *et al* (2015); Verd *et al* (2016)). Therefore, we asked whether Cad affects the damped oscillator mechanism regulating gap genes in *D. melanogaster* in a way that is equivalent to its effect on pair-rule oscillations in *T. castaneum*.

We assessed the regulatory role of Cad by multiplying its concentration profile with different constant scaling factors and measuring the dynamics and extent of gap domain shifts in the resulting simulations (Fig. 4A). This reduces Cad levels throughout space and time without affecting the overall shape of its profile. Our results reveal that the Kr-Gt border interface (Fig. 4A, inset) starts out at the same position, regardless of Cad concentration (Fig. 4A, time class C13). This corroborates earlier analyses which suggest that maternal Hb (not Cad) is the main morphogen in the posterior of the embryo (Struhl *et al* (1992); Manu *et al* (2009a); Jaeger (2011); Verd *et al* (2016)). Between C13 and T1, however, boundary positions diverge: gap domain shifts are slower for lower levels of Cad. From T1 onwards, shift rates become more or less independent of Cad concentration and boundary positions move in parallel in different simulations for the rest of the blastoderm stage (Fig. 4A). Our modelling results are confirmed by experiments showing that mutants lacking maternal *cad* show delayed shifts of the abdominal Kni and posterior Gt domains (Wotton *et al* (2015)). Taken together, this evidence suggests that Cad positively regulates the velocity of gap domain shifts during early

blastoderm stages in *D. melanogaster*, analogous to its positive correlation with pair-rule wave frequency in *T. castaneum*.

Cad regulates the rate and extent of gap domain shifts by altering the fast-slow dynamics of the gap gene damped oscillator (Fig. 4B–D and Fig. S3). While the direction of the flow remains largely constant across different levels of Cad, its magnitude changes significantly (Fig. S3). Most importantly, the magnitude of the flow in the area of the Kr-Kni plane around the origin is strongly reduced at early stages (Fig. 4B–D, time class C12). At later stages, when wild-type Cad levels decrease (and thus the magnitude of the difference between Cad levels in both simulations also decreases), differences are more subtle (Fig. 4B–D, time class T8). The altered early flow explains the slower initial build-up of Kr and Kni at low Cad, while later shift dynamics are similar, independent of Cad level. As a result of the altered early flow, the "radius" of the spiral trajectories decreases as Cad concentration is reduced. Counterintuitively, progress along these tightened spirals is much slower than in simulations with wild-type levels of Cad due to weaker flow in regions of phase space near the origin (compare Figures S. S2 and S. S4). Slow progress means a delayed switch from the Kr-Kni to the Kni-Gt plane, which results in the decrease in shift velocity for the Kr-Gt interface shown in Fig. 4A.

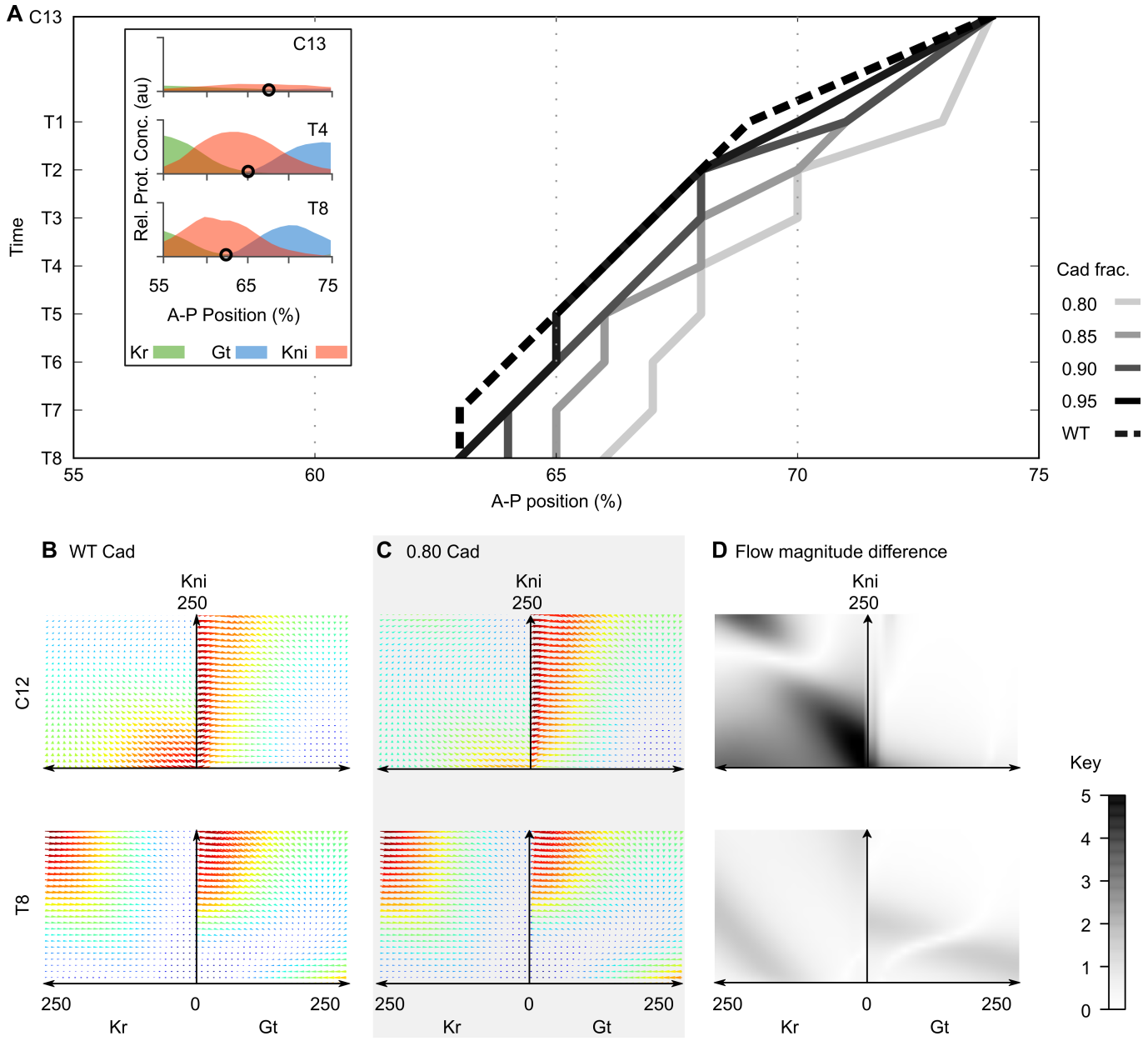

Figure 4: **Caudal levels modulate the initial velocity of gap domain shifts in *D. melanogaster* A** Space-time plot shows temporal shift of the Kr-Gt border interface in simulations with variable levels of Cad (see key and main text). Reduced levels of Cad imply slower shift between C13 and T1. Y-axis represents time (increasing downwards). Inset shows posterior gap gene expression data at time classes C13 and C14A-T4 and -T8. Black circles mark the Kr-Gt border interface. Y-axes show gap protein concentration in arbitrary units (au). X-axes represent % A–P position (where 0% is the anterior pole). **B, C** Stereotypical fast-slow dynamics for posterior nuclei simulated with a wild-type (WT) Cad profile and with a Cad profile multiplied by a factor of 0.8. Unfolded, two-dimensional projections of the Kr-Kni and Kni-Gt planes are shown as in Fig. 3C at C12 and C14A-T8. Coloured arrows indicate magnitude and direction of flow. **D** Grey shading indicates differences of flow magnitude between **B** and **C** (see key). Changes in flow direction are small (see Fig. S3). See Materials and Methods for time classes, and main text for further details.

Conclusions

In this paper, we show that a damped oscillator mechanism—with excitable, relaxation-like behaviour—underlies robust segmental patterning of the long-germband insect *D. melanogaster*. Even though they are not periodic, kinematic shifts of gap gene expression domains are an emergent property of temporally regulated gene expression driven by oscillatory dynamics. In this sense, they are equivalent to the travelling waves of gene expression involved in vertebrate somitogenesis (Palmeirim *et al* (1997); Oates *et al* (2012)) and short-germband arthropod segmentation (Chipman *et al* (2004); Sarrazin *et al* (2012); El-Sherif *et al* (2012); Brena and Akam (2013); El-Sherif *et al* (2014)). This lends support to the notion that regulatory dynamics of segmentation gene expression in long- and short-germband insects are much more similar than is evident at first sight (Tautz (2004)).

While oscillatory mechanisms are involved in both long- and short-germband segmentation, it is important to stress that the factors constituting each particular regulatory system are different. Shifting gap domains play a central role in segmental patterning in *D. melanogaster* by directly regulating stripes of pair-rule gene expression. Posterior pair-rule stripes also exhibit anterior shifts in this species, which are produced by, and closely reflect, the expression dynamics of the gap-gene damped oscillator (Surkova *et al* (2008)). In contrast, gap genes play a much less prominent role in patterning posterior segments in short-germband arthropods. Instead, periodic kinematic waves of pair-rule gene expression are thought to be generated by negative feedback between the pair-rule genes themselves (in *T. castaneum*, Choe *et al* (2006)), or by an intercellular oscillator driven by Notch/Delta signalling (in cockroaches, Pueyo *et al* (2008), and centipedes, Chipman *et al* (2004); Brena and Akam (2013)).

The evolutionary transition from short- to long-germband segmentation in dipterans must have involved the recruitment of gap genes for pair-rule gene regulation, to replace the ancestral oscillatory mechanism (Peel (2004); Peel *et al* (2005); Peel (2008); Jaeger (2011)). A similar recruitment event has occurred convergently in hymenopterans (Pultz *et al* (2005); Lynch *et al* (2006); Olesnicky *et al* (2006); Brent *et al* (2007); Wilson *et al* (2010)), indicating that this transition is relatively straightforward to achieve. However, the mechanistic details of how it occurs remain unclear. Traditionally, long- and short-germband modes of patterning have been assumed to be mutually exclusive in any given region of the embryo. In contrast, our results suggest that the replacement process could have occurred gradually along the A–P axis, gap- and pair-rule oscillators coexisting temporarily, which would greatly facilitate the transition. In this scenario, gap genes "take over" pair-rule driven oscillatory patterning in the posterior, and later convert to a more switch-like static patterning mode, as observed in the anterior of the *D. melanogaster* embryo (Jaeger *et al* (2004a); Surkova *et al* (2008); Manu *et al* (2009a); Verd *et al* (2016)). This is tentatively supported by the fact that the spatial extent of the posterior region, which is patterned by shifting gap domains, differs between dipteran species (García-Solache *et al* (2010); Wotton *et al* (2015)).

Seen from another angle, our results imply that equivalent regulatory dynamics (travelling waves of gene expression) can be produced by drastically different oscillatory mechanisms. The use of divergent regulatory mechanisms to independently pattern identical expression domains appears to be very common (see, for example, Frankel *et al* (2010); Perry *et al* (2011); Fujioka and Jaynes (2012); Cannavò *et al* (2016)). Indeed, the relative contribution of different mechanisms may evolve over time, with little effect on downstream patterning (Wunderlich *et al* (2015)). This type of compensatory evolution is called developmental system drift (Weiss and Fullerton (2000); True and Haag (2001); Weiss (2005); Haag (2007); Pavlicev and Wagner (2012)). It has recently been shown to occur extensively in the evolution of the dipteran gap gene system (Wotton *et al* (2015); Crombach *et al* (2016)). System drift provides the necessary conditions that enable the facilitated gradual transition between different regulatory mechanisms described above.

Even though the core mechanisms that generate oscillatory behaviour differ, some aspects of segmentation gene regulation are strikingly similar between long- and short-germband insects. In both *D. melanogaster* and *T. castaneum*, the speed at which gene expression waves travel through the tissue are positively correlated with the concentration of Cad in the posterior of the embryo (our results and El-Sherif *et al* (2014); Wotton *et al* (2015); Verd *et al* (2016)). Cad also appears to control temporal aspects of gap gene regulation in centipedes Chipman *et al* (2004); Brena and Akam (2013)). From this, we conclude that the role of Cad in regulating oscillatory dynamics is highly conserved. While Cad acts at the level of the pair-rule

genes in centipedes and *T. castaneum*, it exerts its effect primarily through regulating gap domain shifts in *D. melanogaster*. Interestingly, even in this long-germband insect, Cad has been shown to retain direct regulation of pair-rule gene expression (Macdonald *et al* (1986); La Rosée *et al* (1997); Häder *et al* (1998); Dearolf *et al* (1989); Moreno and Morata (1999); Olesnicky *et al* (2006)). This provides further evidence for the recruitment of gap genes into a conserved segmental regulatory cascade involving Cad-mediated regulation of oscillatory pair-rule dynamics.

Our insights into the role of Cad in regulating the gap-gene damped oscillator has further implications. Travelling waves of gene expression that narrow and slow down over time are involved in both arthropod segmentation and vertebrate somitogenesis. It has long been recognised that these expression dynamics imply differential regulation of the rate of an oscillatory process along the A–P axis (Palmeirim *et al* (1997)). However, mechanistic explanations for this phenomenon remain elusive. A number of recent models simply assume that the concentration of some posterior morphogen determines the period of cellular oscillators, without investigating how this might arise (see, for example, Giudicelli *et al* (2007); Morelli *et al* (2009); El-Sherif *et al* (2014)). Experimental evidence from vertebrates suggests alteration of protein stability or translational time delays as a possible mechanism (Ay *et al* (2014); Schröter *et al* (2012)). In contrast, our dynamical analysis illustrates how slowing (damped) oscillations can emerge directly from the intrinsic regulatory dynamics of a transcriptional network, without altering rates of protein synthesis or turnover. A similar mechanism, based on intrinsic oscillatory dynamics of a gene network, was recently proposed for vertebrate somitogenesis (Cotterell *et al* (2015)). It will be interesting to investigate which specific regulatory interactions mediate the effect of Cad on the *T. castaneum* pair-rule gene oscillator.

In summary, we have shown that oscillatory mechanisms of gene regulation are not exclusive to short-germband segmentation. The spatial pattern of gap gene expression in the posterior region of the *D. melanogaster* embryo also emerges from a temporal sequence of regulatory dynamics driven by a damped oscillator. This results in the observed anterior shifts of gap domains. We suggest that the dynamic nature of posterior gap gene patterning is a consequence of the context in which it evolved, and that two different oscillatory mechanisms may have coexisted during the transition from short- to long-germband segmentation. Studies using genetics and data-driven modelling in non-model organisms will reveal the precise nature of the regulatory changes involved in this transition (Crombach *et al* (2014); Wotton *et al* (2015); Crombach *et al* (2016)). Given the insights gained through its application to gap gene patterning in *D. melanogaster*, phase space analysis will provide a suitable dynamic regulatory context in which to interpret and analyse these future results.

Materials and Methods

The gene circuit model

The model used in this study is a diffusion-less version of non-autonomous gap gene circuits published in Ashyraliyev *et al* (2009). It consists of a one-dimensional row of nuclei along the A–P axis. Continuous dynamics during interphase alternate with discrete nuclear divisions. The full spatial range of the model covers the trunk region of the embryo between 35 and 92% A–P position; our analysis focuses on the posterior region between 55% and 73% A–P position, excluding the terminal region of the embryo. We model the last two cleavage cycles of the blastoderm stage (C13 and C14A) up to the onset of gastrulation; C14A is subdivided into eight equally spaced time classes (T1–T8). Division occurs at the end of C13.

The state variables of the system represent the concentrations of proteins encoded by gap genes *hb*, *Kr*, *gt*, and *kni*. The concentration of protein a in nucleus i at time t is given by $g_i^a(t)$. Change in protein concentration over time occurs according to the following system of non-autonomous ordinary differential equations:

$$\frac{dg_i^a(t)}{dt} = R^a \phi(u^a) - \lambda^a g_i^a(t) \tag{1}$$

where R^a and λ^a are rates of protein production and decay, respectively. ϕ is a sigmoid regulation-expression function used to represent the saturating, coarse-grained kinetics of transcriptional regulation. It is defined

as

$$\phi(u^a) = \frac{1}{2}\left(\frac{u^a}{\sqrt{(u^a)^2+1}} + 1\right) \tag{2}$$

where

$$u^a = \sum_{b\in G} W^{ba} g_i^a(t) + \sum_{m\in M} E^{ma} g_i^m(t) + h^a \tag{3}$$

The set of trunk gap genes is given by $G = \{hb, Kr, gt, kni\}$, and the set of external (maternal) regulatory inputs by $M = \{\mathrm{Bcd}, \mathrm{Cad}\}$. Concentrations of maternal regulators g_i^m are interpolated from quantified spatio-temporal protein expression data (Surkova *et al* (2008); Pisarev *et al* (2009); Ashyraliyev *et al* (2009)). Changing maternal protein concentrations mean that the parameter term $\sum_{m\in M} E^{ma} g_i^m(t)$ is time-dependent, which renders the model non-autonomous.

Interconnectivity matrices W and E represent the nature and strength of regulatory interactions between gap genes, and from external maternal inputs, respectively. Matrix elements w^{ba} and e^{ma} are regulatory weights. They summarize the effect of regulator b or m on target gene a, and can be positive (representing an activation), negative (repression), or near zero (no interaction). h^a is a threshold parameter representing the basal activity of gene a. The system of equations (1) governs regulatory dynamics during interphase; R^a is set to zero during mitosis.

Model fitting and selection

We obtain values for parameters R^a, λ^a, W, E, and h^a by fitting the model to data (across its full spatial range) (Reinitz and Sharp (1995); Jaeger *et al* (2004b); Ashyraliyev *et al* (2009); Crombach *et al* (2012)). Details of model fitting and selection of solutions are described in Verd *et al* (2016). Briefly: model equations (1) are solved numerically using an adaptive step-size solver (Ashyraliyev *et al* (2009)). The resulting model output is compared to a quantitative data set of spatio-temporal gap protein profiles (Surkova *et al* (2008); Pisarev *et al* (2009)) using a weighted least squares cost function (Ashyraliyev *et al* (2009)). This cost function is minimised using parallel Lam Simulated Annealing (pLSA) (Chu *et al* (1999)). Optimisation was performed on the Mare Nostrum cluster at the Barcelona Supercomputing Centre (http://www.bsc.es). Fitting solutions were selected for further analysis as described (Crombach *et al* (2012); Verd *et al* (2016)). The resulting diffusion-less, non-autonomous gene circuits accurately reproduce gap gene expression (Fig. 1A). For parameter values of the best-fitting solution, see Verd *et al* (2016).

Model analysis

We use a graphical approach (Strogatz (2014)) to characterise time-variable phase space geometry in a non-autonomous gap gene circuit as previously described in Verd *et al* (2014). Briefly: we generate instantaneous phase portraits (Collier *et al* (1996); Verd *et al* (2014)) for each nucleus at 10 time points: C13, C14A/T1–8, and gastrulation time; this is achieved by keeping all time-dependent parameter values constant at each time point. We then calculate the position of steady states in phase space using the Newton-Raphson method (Conte and de Boor (1980); Press *et al* (1996)). Steady states are classified into saddles and attractors (including spiral sinks) by eigenvalue analysis to determine their stability (Strogatz (2014)). Since nuclei express a maximum of three trunk gap genes over the developmental time covered by our model, we can visualise phase space geometry (attractors, their basins, and the flow of the system) by two- or three-dimensional projections of the four-dimensional phase portrait.

Acknowledgements

We would like to acknowledge Nick Monk for countless discussions and help with the analysis of non-autonomous gene circuits. We thank Anna Kicheva for critical reading and comments that significantly improved our initial drafts of this paper. James Sharpe, Jordi García-Ojalvo, Karl Wotton, Eva Jiménez-Guri,

Astrid Hoermann, Hilde Janssens, Barbara Negre, Damjan Cicin-Sain and Alba Jiménez-Asins patiently and consistently provided guidance and intellectual stimulation during this project. To them, thank you! The authors thankfully acknowledge the computer resources, technical expertise and assistance provided by the Barcelona Supercomputing Center—Centro Nacional de Supercomputación. BV was supported by a "la Caixa" fellowship, and a Writing-up Fellowship at the KLI Klosterneuburg. The research group of JJ was supported by the MEC-EMBL agreement for the EMBL/CRG Research Unit in Systems Biology, European Commission grant FP7-KBBE-2011-5/289434 (BioPreDyn), and grants BFU2009-10184 and BFU2012-33775 from MINECO. JJ thanks the Wissenschaftskolleg zu Berlin (Wiko) for a 10-month fellowship in 2014/15. The Centre for Genomic Regulation (CRG) acknowledges support from MINECO, "Centro de Excelencia Severo Ochoa 2013- 2017," SEV-2012-0208.

Author Contributions

BV and JJ designed the study; EC suggested Cad simulation experiments; BV developed the methodology and performed the analysis; AC performed model fits; BV, JJ and EC performed biological interpretation of the results; BV and JJ wrote the paper with additional contributions from AC and EC.

Supplementary Figures

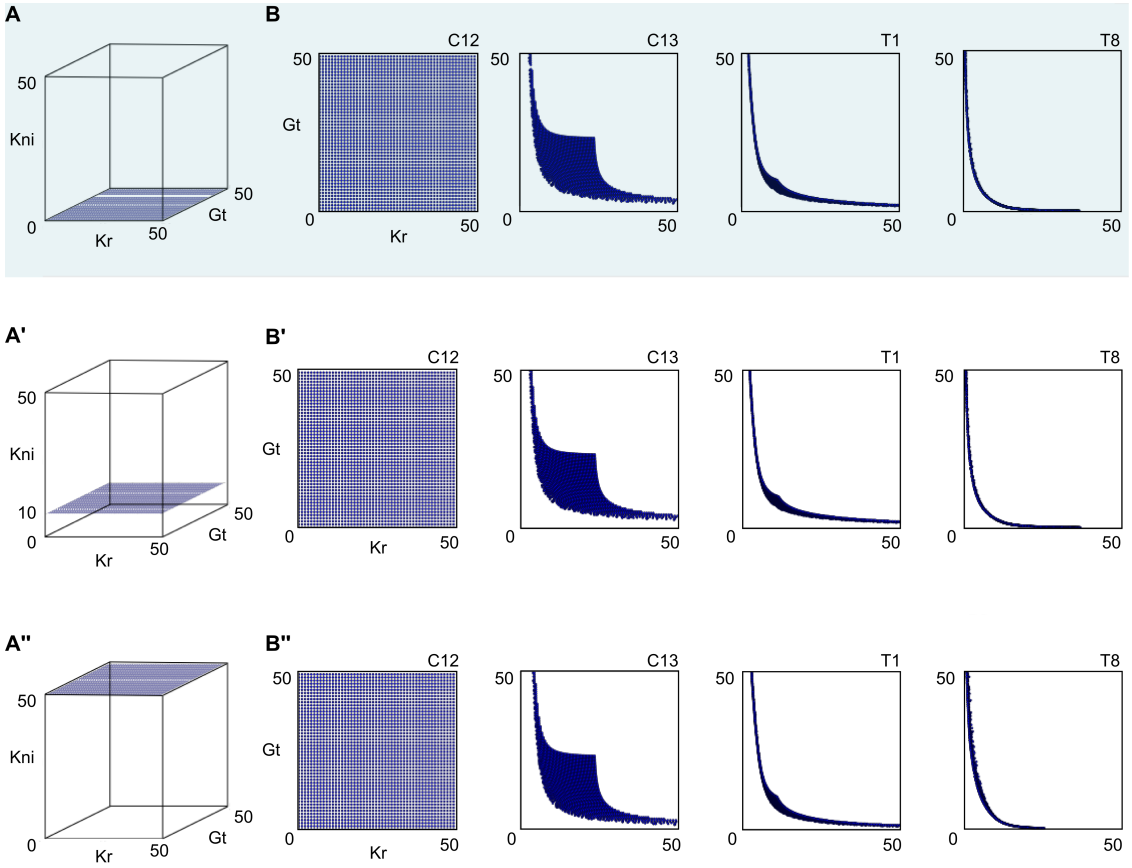

Figure S1: **Canalising properties of the gap gene damped oscillator.** We simulate the non-autonomous diffusion-less circuit in nucleus at 59% A–P position with Kni concentration fixed to zero (**A, B**, as in Fig. 3A, B), fixed to 10 (**A', B'**), and fixed to 50 (**A", B"**), and a set of initial conditions that are regularly distributed on the Kr-Gt plane. **A–A"** Initial conditions shown in blue, embedded within the three-dimensional Kr-Kni-Gt space. **B–B"** Two-dimensional projections of the Kr-Gt plane show converging system states (in blue) at C12, C13, C14A-T1, and -T8. See Materials and Methods for time classes, and text of the main paper for further details.

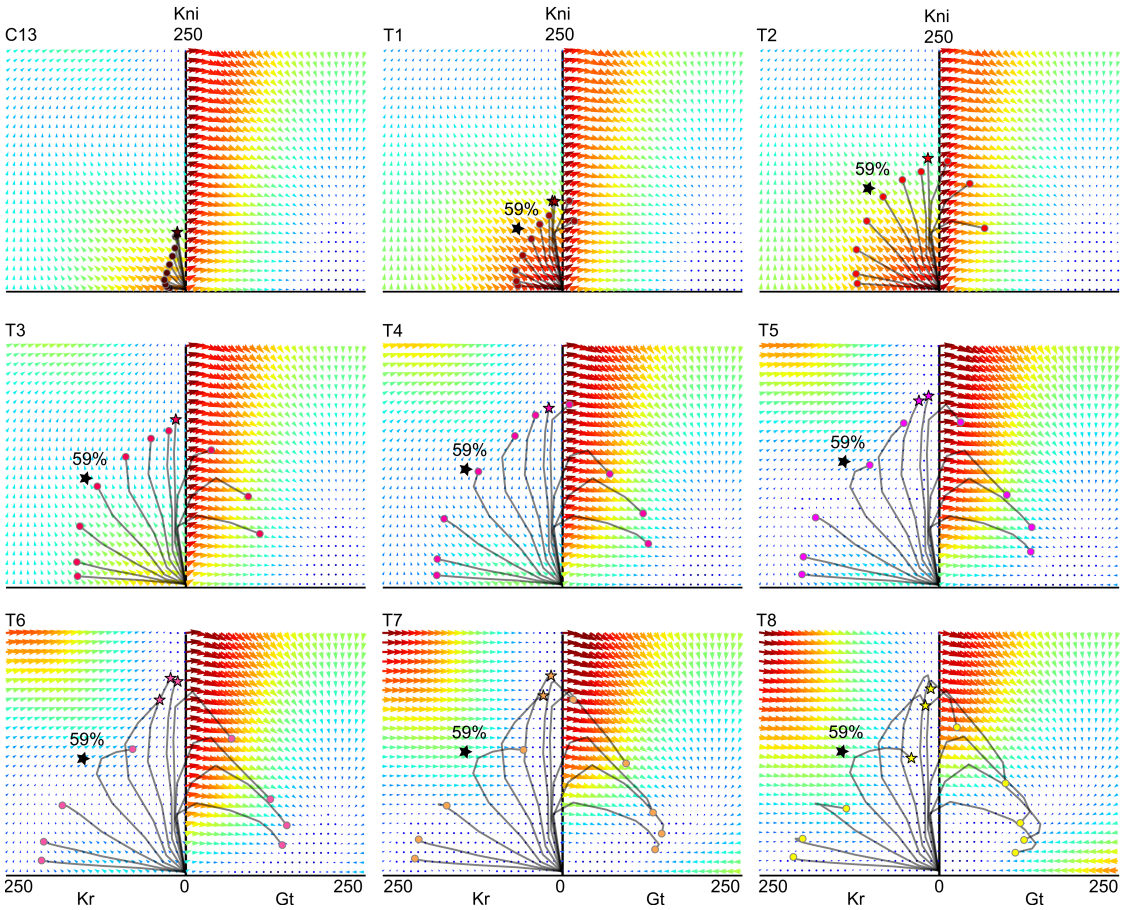

Figure S2: **Relaxation-like behaviour of the gap gene damped oscillator.** Fast-slow dynamics in posterior nuclei are caused by relaxation-like behaviour. Unfolded, two-dimensional projections of the Kr-Kni and Kni-Gt planes are shown as in Fig. 3C at time classes C13–C14A-T8. Coloured arrows indicate magnitude and direction of flow: large red arrows represent strong flow, small blue arrows represent weak flow. Trajectories of posterior nuclei are superimposed on the flow (shown as black lines). Small coloured circles at the end of trajectories indicate current state at each time point. Stars mark trajectories experiencing a positive Gt-component of the flow. See Materials and Methods for time classes, and main text for further details.

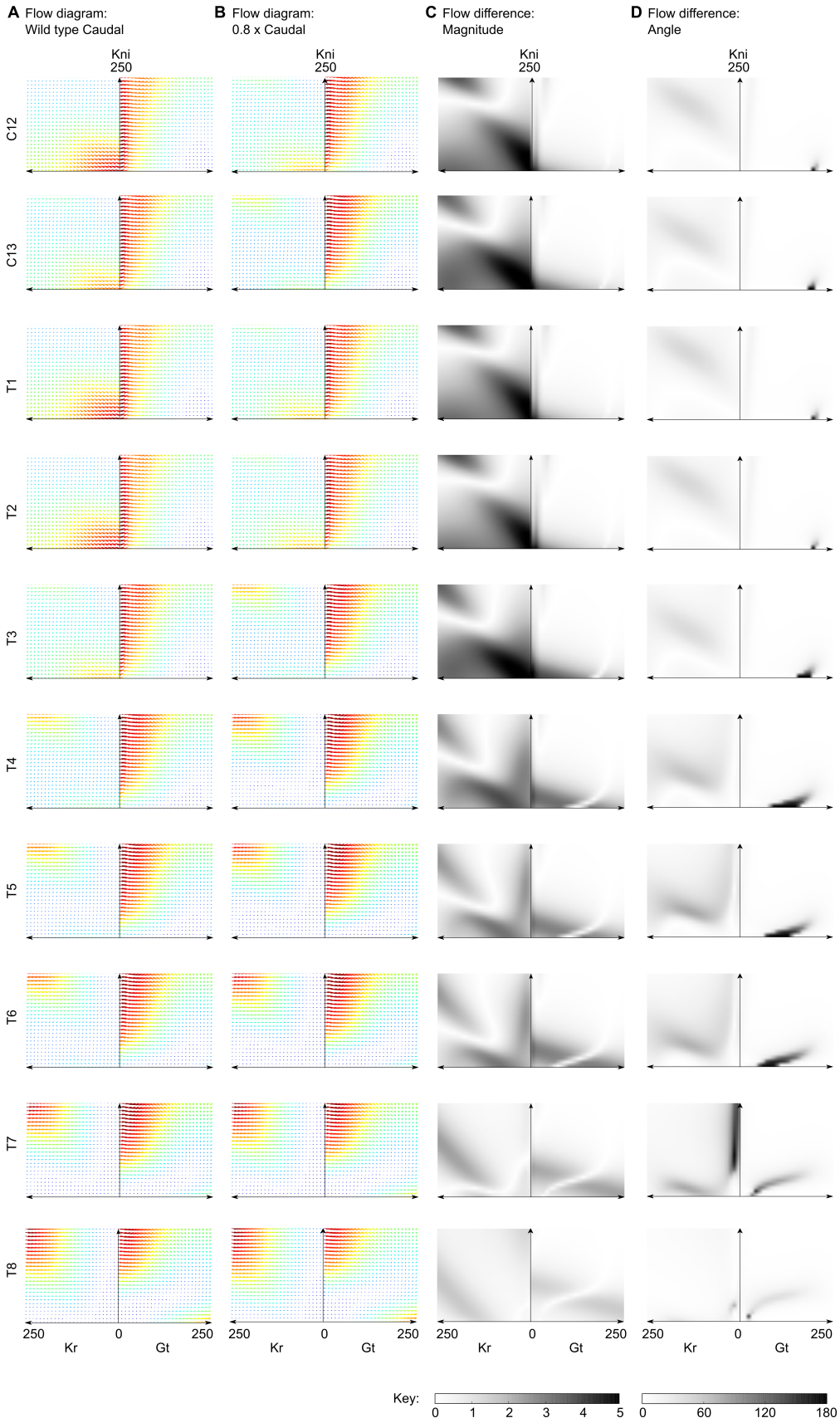

Figure S3: (Caption next page.)

Figure S3: Caudal levels modulate the initial velocity of gap domain shifts in *D. melanogaster*. **A, B** Plots with coloured arrows indicate flow in a simulation with wild-type (WT) levels of Cad (**A**), and a simulation with 0.8x Cad (**B**. Unfolded, two-dimensional projections of the Kr-Kni and Kni-Gt planes are shown as in Fig. 4B and C for time classes C12–C14A-T8. Coloured arrows indicate magnitude and direction of flow. Grey shading indicates differences of flow magnitude (**C**) and direction (**D**) (see keys). See Materials and Methods for time classes, and main text for further details.

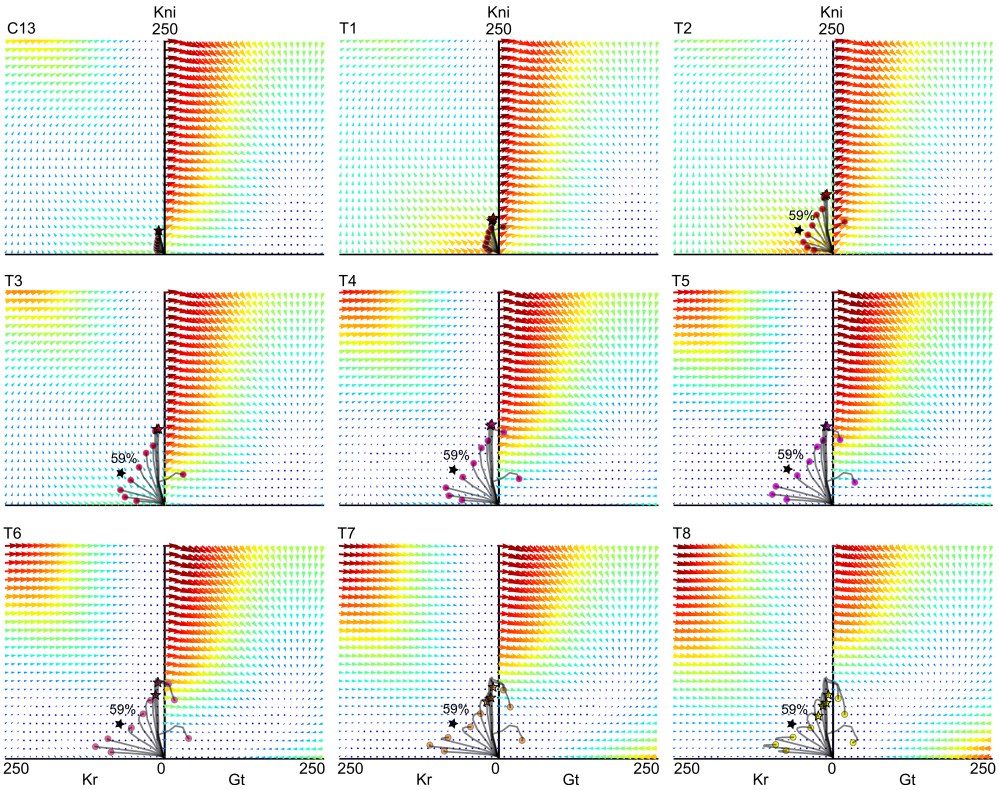

Figure S4: **Caudal levels modulate the fast-slow dynamics of the gap gene damped oscillator.** Flow and trajectories in a simulation with 0.8x scaled Cad. Unfolded, two-dimensional projections of the Kr-Kni and Kni-Gt planes are shown as in Supplementary Fig. S2 at time classes C1–C14A-T8. Coloured arrows indicate magnitude and direction of flow: large red arrows represent strong flow, small blue arrows represent weak flow. Trajectories of posterior nuclei are superimposed on the flow (shown as black lines). Small coloured circles at the end of trajectories indicate current state at each time point. Stars mark trajectories experiencing a positive Gt-component of the flow. See Materials and Methods for time classes, and main text for further details.

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