Developmental Biology

The embryonic role of juvenile hormone in the firebrat, *Thermobia domestica*, reveals its function before its involvement in metamorphosis

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Abstract

To gain insights into how juvenile hormone (JH) came to regulate insect metamorphosis, we studied its function in the ametabolous firebrat, *Thermobia domestica*. Highest levels of JH occur during late embryogenesis, with only low levels thereafter. Loss-of-function and gain-of-function experiments show that JH acts on embryonic tissues to suppress morphogenesis and cell determination and to promote their terminal differentiation. Similar embryonic actions of JH on hemimetabolous insects with short germ band embryos indicate that JH's embryonic role preceded its derived function as the postembryonic regulator of metamorphosis. The postembryonic expansion of JH function likely followed the evolution of flight. Archaic flying insects were considered to lack metamorphosis because tiny, movable wings were evident on the thoraces of young juveniles and their positive allometric growth eventually allowed them to support flight in late juveniles. Like in *Thermobia*, we assume that these juveniles lacked JH. However, a postembryonic reappearance of JH during wing morphogenesis in the young juvenile likely redirected wing development to make a wing pad rather than a wing. Maintenance of JH then allowed wing pad growth and its disappearance in the mature juvenile then allowed wing differentiation. Subsequent modification of JH action for hemi- and holometabolous lifestyles are discussed.

Significance

The likely action of this sesquiterpene hormone as a morphogenesis-to-differentiation switch in archaic embryos preadapted it for later assuming its function as the *status quo* regulator of insect metamorphosis.

eLife assessment

This **important** study presents findings regarding the role of Juvenile Hormone in development and cell differentiation in the ametabolous insect Thermobia domestica, providing an in-depth analysis of JH's roles in a member of this basally branching group. The evidence supporting the claims of the authors is **convincing**, drawing on a broad range of approaches and variety of experimental techniques. While the interpretation of this work in the wider context - its relevance for the evolution of metamorphosis - is in some places somewhat speculative, the work will be of interest to evolutionary developmental biologists studying the evolution of metamorphosis, and the evolution of insects in general.

Introduction

Insects first appeared about 400 mya as a group of direct developing arthropods whose hatchlings were miniature versions of the adult except that they lacked the sexual specializations needed for reproduction. Starting from this **ametabolous** life history, insects underwent series of developmental innovations that resulted in their becoming the dominant meso-sized group of animals in most terrestrial and freshwater environments. The first life history change followed the evolution of wings and powered flight (Kukalová-Peck, 1978; Belles, 2019). In this **hemimetabolous** pattern, the hatchling lacked wings as well as genitalia, and these developed as immobile pads during juvenile growth and transformed into functional structures during the molt to the adult. The subsequent step from this “incomplete metamorphosis” to complete metamorphosis involved a redirection of embryogenesis to produce a modified larval form that was adapted to feeding and growth. The transition to the adult form then occurred through a transitional stage, the pupa, thereby establishing the three-part life history diagnostic of the “complete metamorphosis” exhibited by **holometabolous** insects (reviews: Belles, 2020b; Jindra, 2019; Truman and Riddiford, 2002, 2019). Classically, juvenile hemimetabolous stages were called nymphs and juvenile holometabolous stages were called larvae. Although this terminology is somewhat controversial, we will use it throughout this paper.

The sesquiterpene hormone, juvenile hormone (JH), is the “gate-keeper” for metamorphosis. Both nymphs and larvae depend on it to maintain their respective forms (Jindra *et al.*, 2013, 2015). JH has two essential functions: it is required at the start of an ecdysteroid-induced molt to maintain the insect in its current stage (Riddiford, 1976), and its presence during intermolt periods ensures that imaginal discs and primordia remain dormant and do not begin premature morphogenesis to the adult stage (Truman *et al.*, 2006). Besides its function of suppressing metamorphosis, JH is also involved in shaping polymorphisms such as those seen in the castes of social insects (Nijhout and Wheeler, 1982).

The role of JH in the two ametabolous orders, the Archaeognatha (jumping bristletails) and the Zygentoma (silverfish), is poorly understood. In the latter order, JH is involved in egg production in the adult firebrat *Thermobia domestica* (Bitsch *et al.*, 1985), but the only JH-related action seen in the juvenile is the suppression of scale appearance by JH application during the molt from the third to the fourth juvenile stage (Watson, 1967). In crustaceans, the immediate precursor to JH, methyl farnesoate (MF), regulates ovarian maturation (Laufer, *et al.*, 1998). Since insects and other Hexapoda (i.e. Collembola, Protura and Diplura) evolved from crustaceans (Regier et al. 2005; von Reumont et al. 2012), it has been thought that MF and JH may have originally functioned in regulating reproduction and only later became involved in development as insect life histories became more complex (Goodman and Granger, 2005)

Although JH treatment only mildly effects postembryonic development in *Thermobia* (Watson, 1967), it can severely derange embryonic development (Rohdendorf and Sehnal, 1973). These severe embryonic effects in an ametabolous insect suggest that the JH may initially had been an embryonic hormone and later moved into the postembryonic realm to support more complex life histories.

Our study of the JH titer in *Thermobia* shows that the highest concentrations of the hormone occur during late embryogenesis. By a detailed examination of the effects of chemicals that mimic the natural JH or block its production, respectively, we find that JH is necessary for the terminal differentiation and maturation of embryonic tissues. Associated with promoting differentiation, JH also is a potent suppressor of morphogenesis. A comparison of these embryonic functions in *Thermobia* with corresponding functions in embryos from basal hemimetabolous orders indicates that the ability of JH to switch embryonic tissues from morphogenesis to terminal differentiation was in place before the appearance of flight and of metamorphosis. The development of wings and of complex insect life histories involved the reappearance of morphogenesis during postembryonic growth. In hemimetabolous insects postembryonic morphogenesis was principally related to wing development, but in the Holometabola it involved the deferred building of the adult body plan. We think that JH reappeared in the postembryonic domain of these juveniles as a counterforce to morphogenesis so that the latter was suppressed during most of juvenile growth. The disappearance of JH then allowed morphogenesis and the subsequent formation of the adult.

Results

The time-course of embryogenesis in Thermobia

The embryogenesis of *Thermobia domestica* is summarized in **Fig. 1**. At 37°C, the time from egg deposition to hatching is about 11.5 days. A developmental timetable was constructed using 12 hr egg collections and determining the distribution of developmental stages at half day intervals from the midpoint of each collection window (see Methods). Ages are given in days after egg laying (# d AEL). As with insects from the other ametabolous order (the Archaeognatha), *Thermobia* embryos undergo short germ band development (Jura, 1972). An embryonic rudiment forms at the posterior pole of the egg and consists of head and thoracic segments with a terminal growth zone. As abdominal segments are progressively specified, the ventral midline invaginates into the yolk causing the abdomen to fold onto itself, thereby opposing the ventral surfaces of the anterior and posterior segments (**Fig. 1A**). By about 1.5 d AEL, the embryo is evident as a cleared area at the posterior pole of the egg, and by a half day later abdomen formation is finished, and appendage buds are appearing. The dorsal surface of the embryo is open to the yolk and the embryo has an overall S-shape (**Fig. 1A**).

The embryo then begins “zipping up” its dorsal midline starting at the end of the abdomen. The dorsal closure of the abdomen pushes the abdominal tip ventrally and forward as the embryo and its yolk assume a “comma” shape. Growing appendage buds have reached about a third of their final length by this time. Extraembryonic membranes growing up from the lateral sides of the embryo envelop the yolk mass and then, during katatrepsis, they contract to pull the head of the embryo towards the anterior pole, and the embryo rotates to achieve a C-shape. The enclosure of the yolk by the extraembryonic membranes defines provisional dorsal closure. The embryo then begins rapid morphogenetic growth and cell determination. During this phase of organogenesis, the lateral margins of the embryonic thorax extend dorsally to completely enclose the yolk at definitive dorsal closure (about 7.5 d AEL). Having reached its full size, the embryo then undergoes terminal differentiation and maturation over the next 4 days.

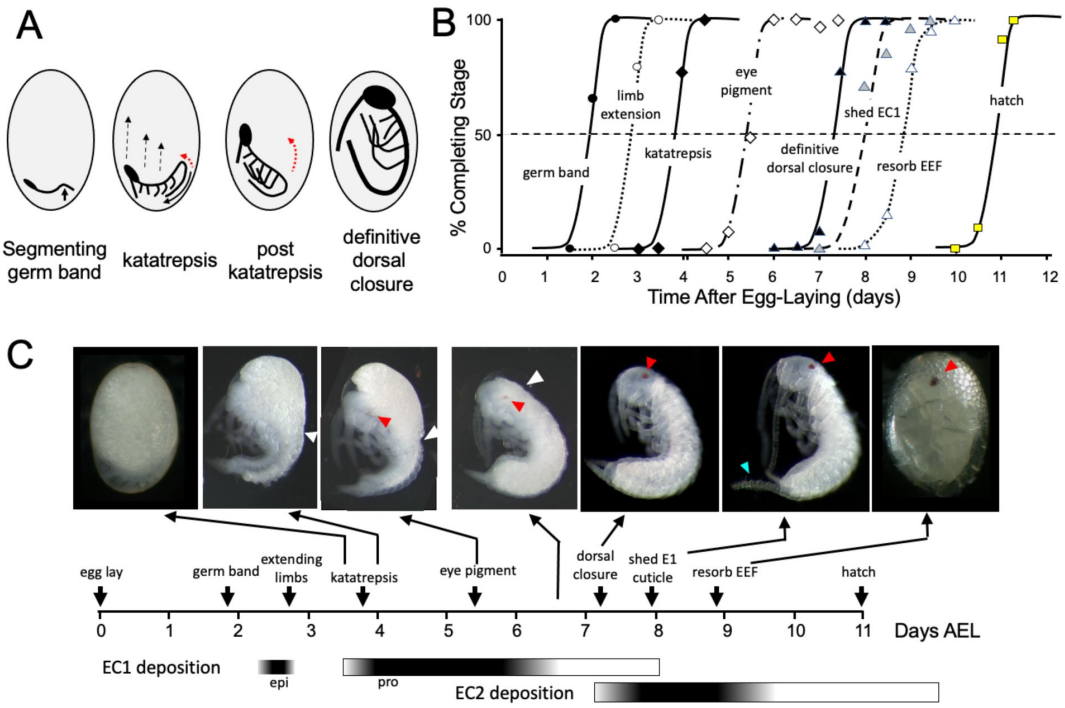

Figure 1.

Timeline of *Thermobia domestica* embryogenesis at 37°C.

(A) Diagrammatic representations of important events in embryogenesis. In the segmenting germ band, the arrow indicates the invagination of the mid-abdominal region into the yolk. By the onset of katatrepsis (Panfilio, 2008), dorsal closure along the abdomen (red arrow) has moved the abdomen ventrally (solid black arrow) and the contraction of the serosa pulls the sides of the embryo towards the anterior pole (dashed black arrows). After katatrepsis the expanding lateral edges of the embryo displace cells of the amnion, gradually zipping up the dorsal thoracic midline (red arrow) until definitive dorsal closure is accomplished. **(B)** Summary of the progression of embryonic development at various times after egg deposition. The interception of each stage with the 50% line (dashed) is the basis for the embryonic timeline in (C). EEF: extraembryonic fluid. **(C)** Timeline of embryonic development based on (B). Micrographs show the appearance of embryos at the indicated times; first and last embryos are covered by the egg chorion. White triangle: progression of dorsal closure; red triangle: eye pigmentation; blue triangle: expanded cerci after shedding of the E1 cuticle. Times of cuticle deposition based on Konopová and Zrzavý, 2005.

Embryogenesis is accompanied by two bouts of cuticle production. The first embryonic (E1) cuticle is deposited after the formation of the segmented germ band. It contains little chitin (see below) and has a fibrous structure (Klag, 1978; Konopová and Zrzavý, 2005) which presumably allows it to stretch to accommodate subsequent embryonic growth. The second embryonic (E2) cuticle starts to be deposited around dorsal closure as the embryo reaches its full size. The E2 procuticle has the lamellar structure (Konopová and Zrzavý, 2005) typical of most insect cuticles (Neville, 1975) and serves as the cuticle of the first juvenile (J1) stage. This cuticle is shed a day after hatching with the start of the J2 stage. Feeding begins in the J3 stage.

JH and ecdysteroid titers during embryogenesis of Thermobia domestica

As in most insects, *Thermobia* produces JH III (Baker *et al.*, 1984). Using the liquid chromatography-mass spectrometric method of Ramirez *et al.* (2020), we measured JH III levels during *Thermobia* embryogenesis at daily intervals starting at 5 d AEL and extending through hatching and the first 10 days of postembryonic life (**Fig. 2A**). Detectable levels of JH III were found at 6 d AEL, and the titer slowly ramped up until an abrupt peak on days 10 and 11. After hatching, JH III fell to low, but detectable, levels through the start of the J4 stage.

Ecdysteroid titers through embryogenesis and the early juvenile instars were measured using the enzyme immunoassay method (Porcheron *et al.*, 1989). As seen in **Fig 2B**, there was a shallow, transient rise in ecdysteroid from 2.5 to 4 d AEL, associated with the time of deposition of the E1 cuticle (Konopová and Zrzavý, 2005). A prominent peak of 20 hydroxyecdysone (20E) then occurred around the time of dorsal closure, coordinated with the production of the E2 cuticle, and another 20E peak occurred just before hatching. We assume that this late embryonic peak is responsible for producing the J2 cuticle. The subsequent ecdysis to the J3 stage is preceded by an increase in 20E one to two days earlier.

Figure 2C summarizes the expression of some endocrine-related transcripts. Using real-time PCR (and the comparative Ct method; Schmittgen and Livak, 2008), we measured transcript levels at half-day intervals through the first half of embryogenesis and then at daily intervals thereafter. Transcripts for the JH receptor, *Methoprene-tolerant* (*Met*), appeared around the time of segmented germ band formation and extended through dorsal closure. *Met* transcript levels declined when the JH III titer spiked. *Krüppel homolog 1* (*Kr-h1*) is a highly conserved gene that is induced by JH (Konopova et al., 2011; Smykal *et al.*, 2014; Belles, 2020a; He and Zhang, 2022). Low levels of *Kr-h1* transcripts were present at 12 hr after egg deposition, but then were not detected until about 6 d AEL when JH-III first appeared. A spike in *Kr-h1* transcripts coincided with the JH III peak at the end of embryogenesis. Myoglianin (myo) is a member of the Transforming Growth Factor-β (TGF-β) family of morphogens (Upadhyay *et al.*, 2017). Its appearance in the last larval or nymphal instar suppresses JH production (Ishimaru *et al.*, 2016; Kamsoi and Belles, 2019; He *et al.*, 2020) and is essential for the onset of metamorphosis. Myo also acts on some target tissues in the last larval instar to make them competent to initiate metamorphosis (Awasaki *et al.*, 2011). *Myo* transcripts appeared in *Thermobia* after formation of the segmented germ band. They peaked during the major phase of embryonic growth, and then were low after definitive dorsal closure.

Effects of suppression of the late embryonic peak of JH

To examine the role of embryonic JH (**Fig. 2A**), we treated embryos with 7-ethoxyprecocene (7EP), a drug that suppresses JH production (Bowers and Martinez-Pardo, 1977; Aboulafia-Baginsky *et al.*, 1984). As seen in **Fig. 3A**, treatment of young juvenile *Thermobia* with 7EP markedly suppressed their production of JH III. Also, application of 7EP to embryos at 6 d AEL, prior to the onset of JH secretion, prevented the appearance of *Kr-h1* transcripts, but the latter could then be induced by treatment with 1 ng of pyriproxyfen, a JH mimic (JHm) (**Fig. 3B**). Therefore, 7EP is effective in suppressing JH synthesis in *Thermobia*.

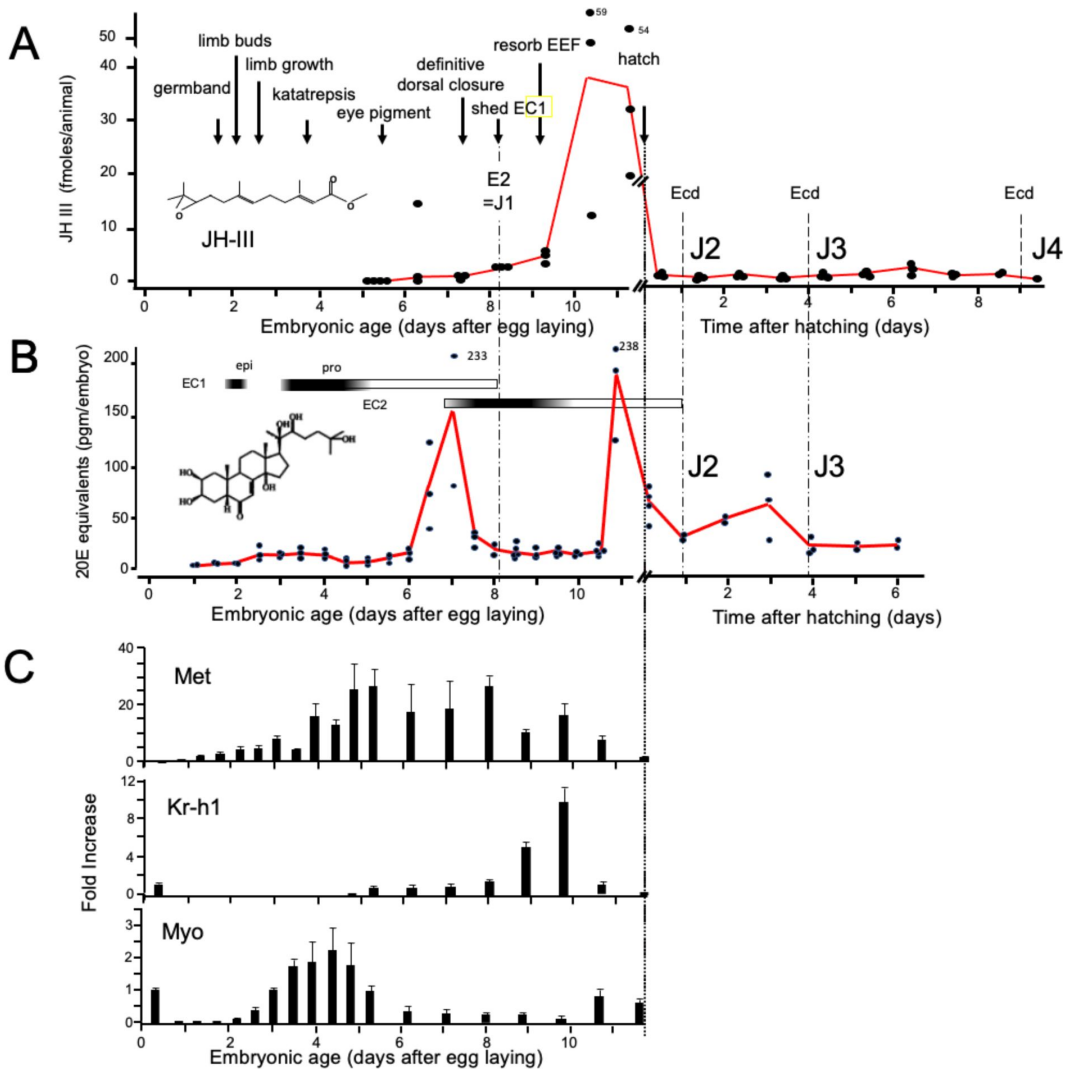

Figure 2.

Titers of hormones and hormone related gene transcripts during embryogenesis of *Thermobia domestica.*

(A) Titer of juvenile hormone III (JH-III) during the last 60% of embryogenesis and the first eight days of juvenile life. The timing of various milestones of embryonic development are noted for this panel and those below. ecd: ecdysis; J#: start of second, third and fourth juvenile instars. **(B)** The ecdysteroid titer in 20-hydroxyecdysone (20E) equivalents during embryogenesis and the first six days of juvenile life. Dark bars indicate the approximate time of deposition of the first embryonic (EC1) epicuticle and procuticle, and the second (EC2) embryonic cuticle (based on Konopová and Zrzavý, 2005). epi: epicuticle deposition, pro: procuticle deposition. **(C)** The relative levels of transcripts of the JH receptor, *Methoprene-tolerant* (*Met*), the JH response gene *Krüppel homolog 1* (*Kr-h1*), and the TGF-β family member *Myoglianin* (*Myo*) based on real-time PCR of timed embryos. Expression of each gene is related to the 12 hr timepoint which is given the value of 1. Each bar shows the mean (+/- S.D.) for three biological replicates.

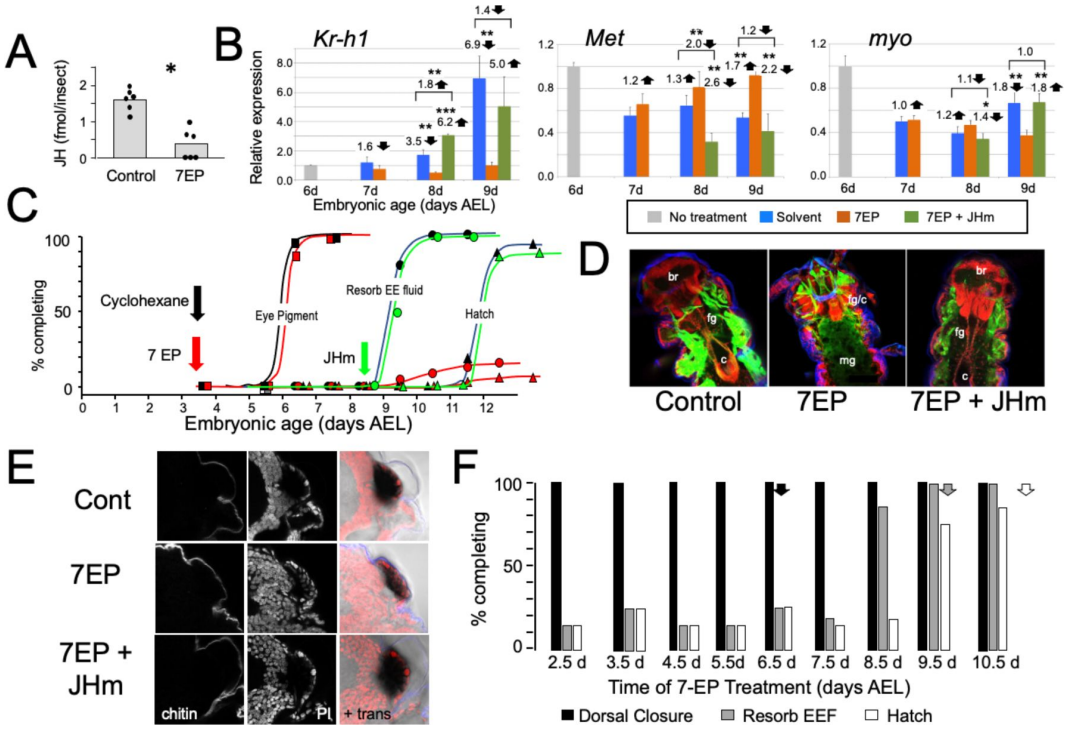

Figure 3.

The effects of suppression of JH production on the embryonic development of *Thermobia*.

(A) Compared with solvent alone (Control), treatment of stage 2 juveniles with 7-ethoxyprecocene (7EP) resulted in a >75% reduction in JH-III levels as measured on the day after application. **(B)** The effect treating embryos at 6 d AEL with the cyclohexane solvent (blue) or 1 µg 7EP (orange) on their subsequent expression of *Kr*-h1, *Met*, and *myo* over the next three days as revealed by real-time PCR. Sub-groups of 7EP treated embryos were treated with 1 ng JHm at 7 d and measured over the next two days (green). Significant differences determined by t-test: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Numbers above columns indicate fold upregulation (upward arrow) or downregulation (downward arrow) of the two hormone treatments relative to cyclohexane control, or to the effect of JHm rescue to 7EP treated embryos. Each based on three biological replicates. **(C)** A group of 20 embryos were treated with cyclohexane (black) or 1µg 7EP (red) and their subsequent development monitored until hatching. Both groups started eye pigmentation at the same time, but resorption of the extraembryonic fluid and hatching were suppressed in the 7EP group. The latter two events were restored by treating embryos with the 1 ng JHm at 8.5 d AEL (green). **(D)** Confocal sections of the dorsal view of embryos treated as in "C" and examined at the time of hatching of the controls. 7EP treatment prevented extension of the foregut (fg) and crop (c) and the posterior displacement of the midgut (mg). Normal gut development was restored with JHm treatment at 8.5d. br: brain; muscle (green); propidium iodide staining (red). **(E)** Pseudo-transmitted light and confocal sections showing cuticle and nuclei of the eye region of 10 d embryos that had been treated with cyclohexane (control) or 7EP at 5 d AEL. A subset of the latter was then given JHm on day 7.5. Control and JHm-treated embryos show local apolysis of the eye cuticle and expansion of the depth of the eye due to growth of the rhabdoms; embryos treated with 7EP alone failed to show this growth. PI: propidium iodide stain, + trans: pseudo transmitted light. **(F)** The relationship of the final phenotypes of embryos to the time of their treatment with 1 µg of 7EP. Arrows indicate the normal timing of the event. EEF: extraembryonic fluid.

Initially, embryos were treated with 1 μg of 7EP at 3.5 d AEL and monitored daily to track features of development that could be viewed through the eggshell (**Fig. 3C**). Solvent control and 7EP-treated embryos acquired eye pigment and underwent dorsal closure (not shown) at the same time, but the 7EP group failed to resorb their extraembryonic fluid and did not hatch. Fluid resorption and hatching was rescued when these embryos were treated with JHm shortly after dorsal closure.

Dissection of the 7EP-treated embryos showed that they usually did not shed their E1 cuticle or expand their E2 cuticle. After dorsal closure, the foregut normally lengthens as the midgut is displaced posteriorly to the anterior abdomen, but these events did not occur after the 7EP treatment (**Fig. 3D**). In the case of the developing eye, the various ommatidial cell types are present and recognizable by dorsal closure and assume their mature configuration by hatching. Also, by hatching the distal most cells in each ommatidium have detached from their overlying cuticle in preparation for making the cuticular lenses of the J2 stage. Ommatidial maturation and cuticle detachment did not occur after 7EP treatment (**Fig. 3E**). However, the normal maturation of both the eye and the midgut was seen after subsequent application of JHm (**Fig. 3D, E**).

Sensitivity to the suppression of JH synthesis by 7EP treatment did not end in an all-or-none fashion (**Fig. 3F**). Development up through dorsal closure was unaffected, regardless of time of 7EP treatment, resorption of the extraembryonic fluid was suppressed by treatment up until about 8 d, and hatching was blocked until about 9 d AEL. This progressive loss of the effectiveness of suppressing JH biosynthesis suggests that JH does not provide a phasic signal, but rather acts tonically through the end of embryogenesis to bring about terminal differentiation and hatching.

Figure 4A shows that the timing of JHm application was essential for rescuing the developmental block imposed by 7EP. Embryos given 7EP on 3.5 d AEL were then treated with JHm (1 ng of pyriproxyfen) at various days thereafter, and their subsequent time of fluid resorption and hatching determined. The embryos of the group treated on 6.5 d AEL were prior to definitive dorsal closure, and all failed to complete this process. Day 7.5 AEL is about the midpoint for embryos undergoing definitive dorsal closure (**Fig. 1**) and half of the treated group failed to complete dorsal closure while the remainder subsequently resorbed their extraembryonic fluid and hatched. Essentially all the 7EP-treated embryos given JHm on 8.5 d and 9.5 d AEL also showed fluid resorption and hatching. Importantly, the time of fluid resorption and hatching was time-locked to the time of JHm treatment (**Fig. 4A, B**). The 7.5 d AEL group hatched a day earlier than untreated controls, the 8.5 d group hatched the same day as controls, and the 9.5 d group hatched one day later.

Manipulation of JH levels affected the production of *Kr-h1* transcripts. Suppression of JH production also blocked induction of *Kr-h1*, while application of JHm to blocked embryos reinstated elevated *Kr-h1* expression (**Fig. 3C**). Transcripts for *Met*, the JH receptor, show a mild down-regulation when JH III appears late in embryogenesis (**Fig. 2C**). This down-regulation was blunted by suppression of JH synthesis, but then enhanced by application of a JHm. Compared to their peak abundance at mid-embryogenesis, levels of *myo* transcripts were quite low going into the terminal stages of embryogenesis (**Fig. 2C**). These levels were largely unaffected by late manipulations of JH (**Fig. 3B**).

Effects of early treatment with juvenile hormone

Rohdendorf and Sehnal (1973) first showed that treating *Thermobia* embryos with natural JHs and a wide array of synthetic analogs produced a range of embryonic deformities. We initially tested the effectiveness of JH III and its precursor, methyl farnesoate (MF), as well as three commonly used JH mimics, methoprene, hydroprene, and pyriproxyfen (Goodman and Cusson, 2012). When applied at 3 d AEL, all produced a full range of embryonic abnormalities, depending on dosage (data not shown). Between the naturally occurring compounds, JH III was about 8-fold more potent than MF, with an ED_{50} for topical application of 60 ng/egg while MF had

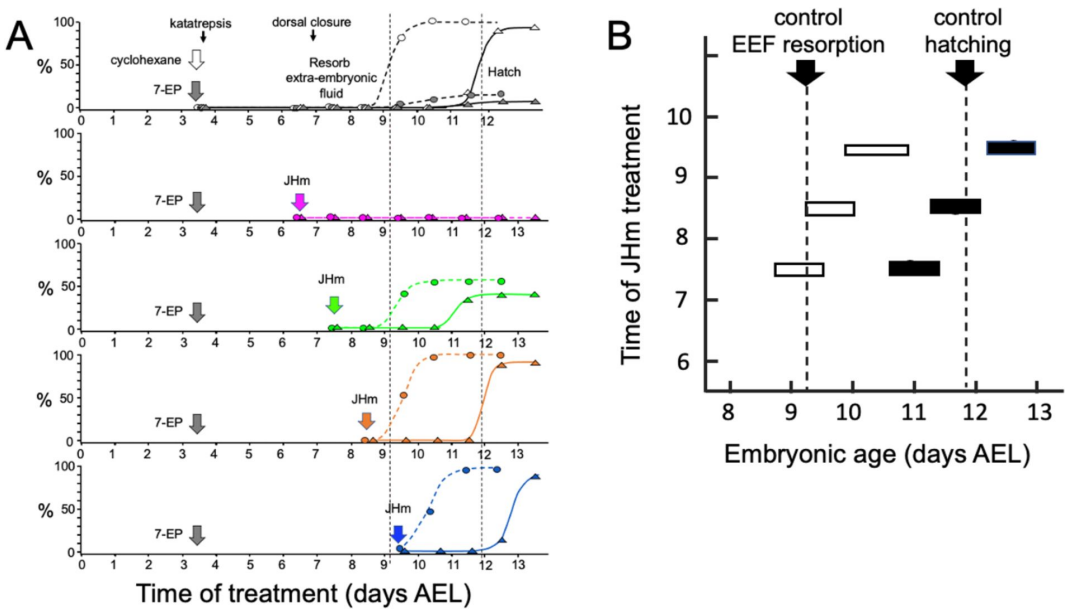

Figure 4.

Time-course of the rescue of 7EP-imposed developmental arrest by treatment with JHm.

(A) Groups of about 20 embryos were treated with cyclohexane (controls) or 1 µg 7EP at d3.5 AEL and then monitored daily for the time of reabsorption of the extraembryonic fluid and hatching. The vertical dashed lines indicate the 50% time for these two developmental events in the control group. Replicate groups were also given JHm (1 ng pyriproxyfen) at the indicated times and their development followed to hatching. **(B)** Summary of the timing of resorption of the extraembryonic fluid (EEF, white bars) and of hatching (black bars) for 7EP-treated embryos, whose development was rescued by JHm treatment at the indicated times.

an ED_{50} of 480 ng/egg. The synthetic JH mimics were about 100 times more potent than JH III. We used pyriproxyfen (referred to as JHm) for all the following studies. The JH receptor has a higher affinity for pyriproxyfen than for JH III or methoprene (Charles *et al*. 2011; Jindra *et al*. 2015).

Figure 5 examines the response of embryos to treatment with different doses of JHm at 1.5 d AEL, when the forming germ band is first evident at the posterior pole of the egg. Embryos were then dissected and scored at 4.5d AEL, about a day after the normal completion of katatrepsis. Embryos treated with the highest doses of JHm (1 to 10 ng/egg) always formed a complete segmented germ band, with its appendage buds. However, the embryos retained a S-shaped posture and stayed at the posterior pole of the egg. They remained open dorsally from the head to the end of the abdomen and subsequent growth was suppressed. The cells of the amnion did not extend to enclose the yolk and these embryos often later sunk back into the yolk. Despite their early arrest, though, they secreted a cuticle over their ventral epidermis (chitin staining in **Fig. 5B**).

Embryos exposed to intermediate doses of JHm (0.3 to 0.03 ng pyriproxyfen) were able to subsequently "zip up" the dorsal midline of their abdomen, which pushed the end of the abdomen ventrally and forward, causing the embryo to assume a "comma" shape just prior to the start of katatrepsis. Subsequent morphogenesis of the head and thorax, though, was suppressed. Chitin-rich cuticle covered the abdomen and the ventral epidermis of the head and thorax. In many cases, the amnion failed to subsequently spread dorsally to enclose the yolk. Sometimes the amnion enclosed the yolk, but the lateral margins of the embryo were not pulled with it so that the yolk ended up as a rounded dorsal lobe with the embryo hanging ventrally in a fluid-filled space (**Fig. 5C**). Embryos treated with lowest doses of JHm (0.01 to 0.001 ng pyriproxyfen) underwent normal katatrepsis and their amnion spread to cover the yolk to establish provisional dorsal closure.

The terminal phenotypes of embryos also varied with the **time** of JHm treatment (**Fig. 6A**). Application to eggs within 12 hr of oviposition was problematic because the cyclohexane-treated controls also showed significant lethality. With older embryos, though, treatment with the solvent alone did not interfere with subsequent development. **Figure 6B** tracks the development of groups of embryos treated with 1 ng pyriproxyfen at various days of embryogenesis and shows that the ability to complete successive "milestones" of development depended on the time of JHm treatment. These developmental milestones lost sensitivity to JHm in the order in which they normally appeared, but the latency between loss of sensitivity and occurrence of the respective event varied (**Fig. 6C**). For example, katatrepsis was blocked by JHm until shortly before the process began, but the ability to suppress production of the eye screening pigment, by contrast, was lost two days before the pigment normally appeared. In *Thermobia*, as in other insects (Friedrich, 2006), the eye primordium makes ommatidia progressively starting at its posterior border. The eye primordium is early in this process at 3.5d AEL, with only the most posterior ommatidia being determined (**Fig. 6D**). Embryos treated at this time subsequently showed screening pigment only in this posterior part of the eye associated with a few proto-ommatidial clusters (**Fig. 6E**). When JH application was delayed by one day, the full primordium had been determined by the time of treatment and a full eye was formed with all its ommatidial clusters (**Fig. 6F**). Thus, JH does not block pigment formation *per se*, but rather it blocks the prior determination of the cell type that will make the pigment. Once determined, these cells subsequently produce pigment regardless of the presence or absence of JH. In the production of the much larger eye of embryos of the locust, *Schistocerca gregaria,* early exposure to JHm similarly arrested the progression of the eye morphogenetic furrow. It also caused the premature maturation of the ommatidia cell types posterior to the furrow (**Fig. 6 – figure supplement 1**).

Exogenous JHm no longer arrested subsequent development if given after about 6 d AEL (**Fig. 6B, C**). This time is just before definitive dorsal closure and subsequent appearance of endogenous JH. Shortly after katatrepsis the amnion encloses the yolk at provisional dorsal closure and these

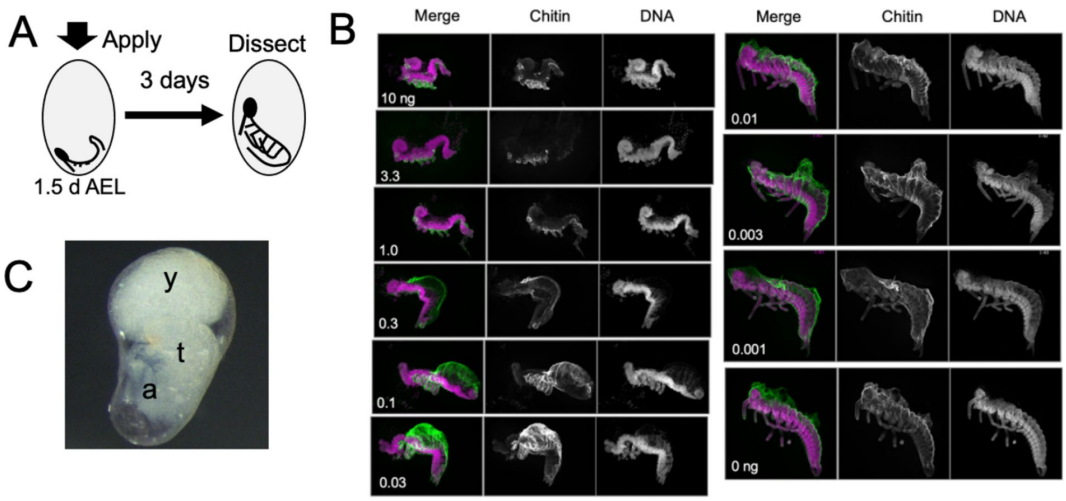

Figure 5.

The response of *Thermobia* embryos to various doses of the JH mimic pyriproxyfen.

(A) Cartoon showing the time of JHm treatment versus the time of dissection. **(B)** Lateral projections of confocal stacks showing the appearance of typical embryos three days after treatment with the indicated dosage of pyriproxyfen. Embryos were stained for DNA (magenta) and chitin (green). The embryos were dissected away from the yolk which caused disruption in the dorsal thoracic and head regions of some embryos. **(C)** Micrograph of an embryo arrested in mid-katatrepsis. During its envelopment of the yolk, the contraction of the amnion segregated the yolk (y) from the embryo which hangs in the ventral half of the egg. t: thorax, a: abdomen.

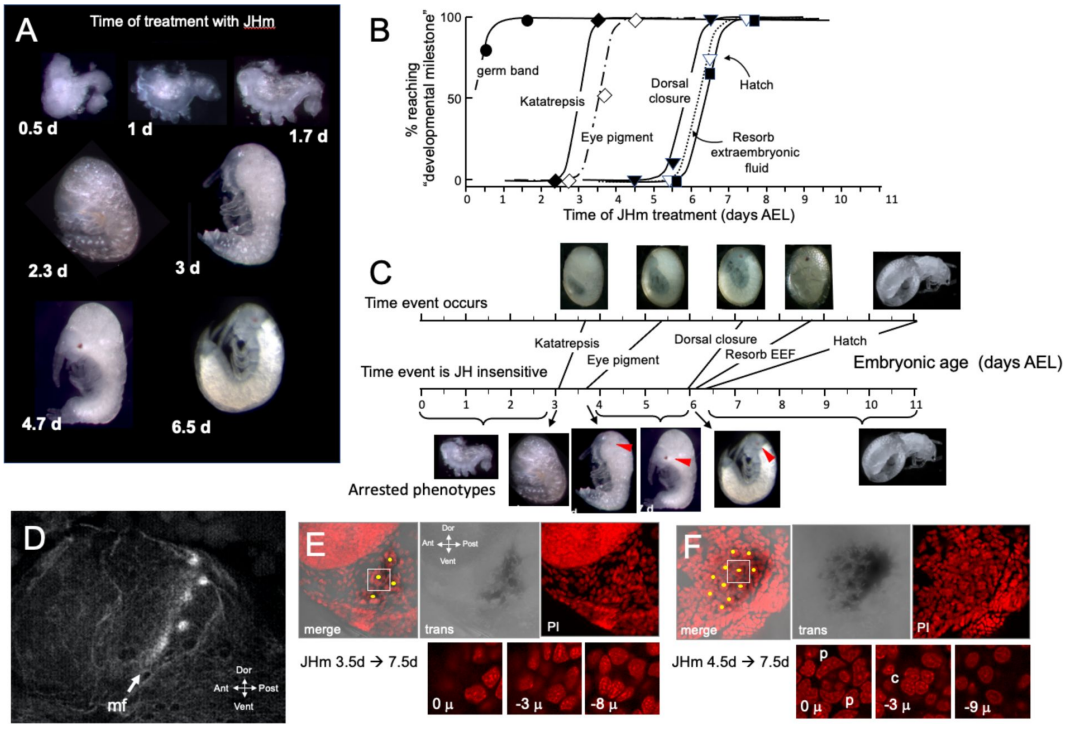

Figure 6.

The response of *Thermobia* embryos to 1 ng JHm given at different times through embryogenesis.

(A) Examples of the terminal phenotypes of embryos resulting from JHm treatment at the indicated times [days after egg laying (AEL)]. Yolk was dissected away from the first three embryos. The remaining embryos had undergone provisional dorsal closure with the amnion enclosing the yolk mass. **(B)** Graph showing when each developmental "milestone" was no longer suppressed by JHm treatment. **(C)** Comparison of when developmental milestones were no longer suppressed by JHm (based on **Fig 1B**) versus their normal time of occurrence. Red triangle in micrograph shows first appearance of eye pigment. **(D)** Confocal image of actin staining showing the state of patterning of the eye primordium at katatrepsis. The morphogenetic furrow (mf) had just started and had organized only the first few posterior ommatidia. **(E, F).** Lateral confocal and pseudo transmitted light images of the eye region of 7.5 d embryos that had been treated with JHm at (E) 3.5 d or (F) 4.5 d AEL. In (E) eye patterning arrested early resulting in only 3-4 proto-ommatidial clusters forming in the posterior margin of the eye primordium. In (F) the entire eye primordium was patterned. Yellow dots identify the center of each forming ommatidium. The insets below show various Z depths of the boxed cluster in the merged image, with "0 µ" being at the surface. Nuclei of identifiable ommatidial cell types can only be recognized in (F). c: quartet of crystalline cone cells, p: crescent-shaped nuclei of the paired cells that secrete the cuticular lens.

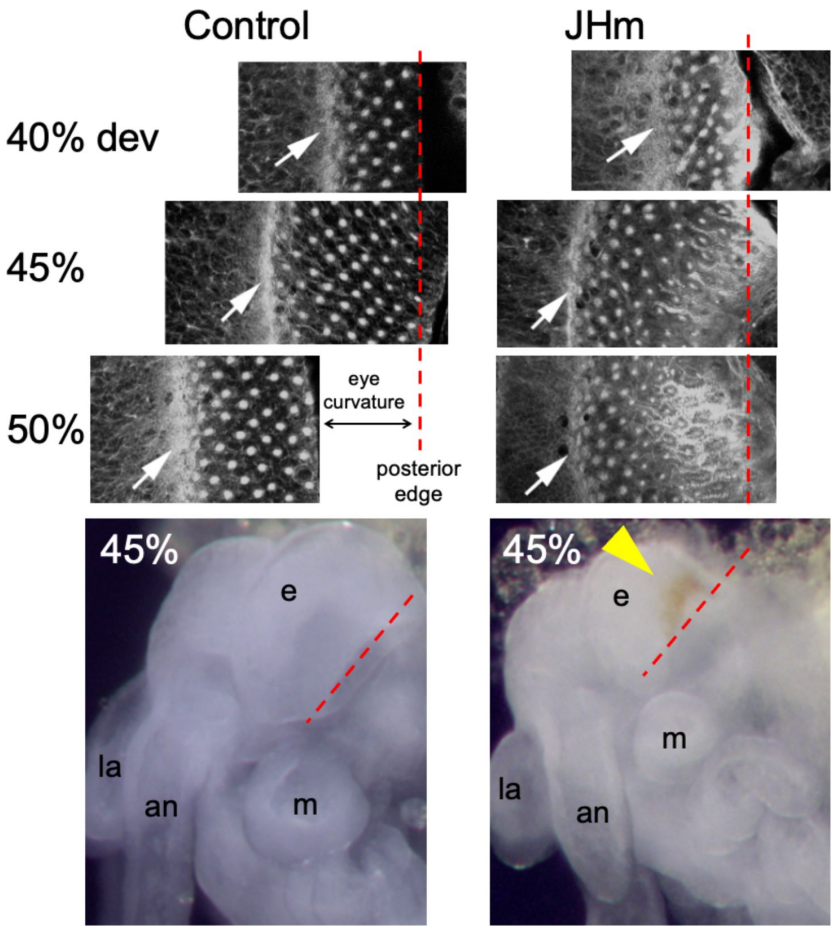

Figure 6_--- Figure Supplement 1.

Confocal images showing the effects of treatment of day 1 *Schistocerca gregaria* embryos with a JHm (pyriproxyphen) versus cyclohexane (control).

Confocal images show eye primordia of embryos stained with fluorescent phalloidin at various times in development showing the progression of ommatidia formation in the wake of the morphogenetic furrow (white arrow). By 50% of embryogenesis the furrow and posterior margin are no longer in the same plane of focus because of the pronounced curvature of the eye; the image has been shifted to accommodate the rows of posterior ommatidia missing from the image. The morphogenetic furrow arrests by 45% in the JHm treated embryos and the posterior rows of ommatidia show autofluorescence due to the premature appearance of screening pigment around each ommatidium. Bottom: at 45% of embryogenesis, premature pigment expression (yellow triangle) is evident in the eye of the JHm treated embryo but not in the control. an: antenna, e: eye, la: labrum, m: mandible. Red dashed line is the posterior border of the developing eye.

amnion cells are gradually replaced by the sides of the embryo until the latter fully enclose the yolk about 3.5 days later. JHm treatment at any time in this interval arrested further replacement. Without successful dorsal closure, the terminal events of fluid resorption and hatching did not occur. The last two events require JH but only after dorsal closure has been completed (**Fig. 4**).

The effect JH on embryonic growth was assessed by treating embryos with JHm at 1.5 d AEL and then using phosphohistone H3 (pHH3; Hendzel *et al*., 1997) expression to measure the mitotic activity in limb buds (**Fig. 7A, B**). At 2.5 d AEL the limb buds of control and treated embryos were of similar size and showed similar levels of pHH3 expression (**Fig. 7B**). All control embryos completed katatrepsis. Their numbers of pHH3 positive cells peaked between 4.5 d and d5.5 d AEL, when their limbs had achieved their full length, and then declined. JHm-treated embryos, by contrast, varied in whether they completed katatrepsis. At 3.5 d AEL, most of the JHm-treated embryos showed numbers of pHH3+ cells like those seen in controls, although two showed a marked reduction. By 4.5 d AEL, all JHm treated embryos showed a mitotic frequency that was only 10-15% of that of controls (**Fig. 7B**). Mitosis in their limbs remained low through subsequent development.

As summarized in **Figures 7C, D**, early JHm treatment sometimes evoked necrosis in the growing limb buds. Necrotic bodies, consisting of highly compacted DNA, were rarely seen in controls at 4.5d and 5.5d AEL. JHm-treated embryos that completed katatrepsis also showed few, if any, necrotic bodies, but those that arrested before or during katatrepsis exhibited moderate to heavy necrosis (**Fig. 7D**). In the most severe cases, the limb degenerated. Limb loss in such embryos was often stochastic, *i.e.*, in a given embryo some limbs were lost while others were maintained in a reduced state. We saw no segmental pattern as to which limbs were maintained and which were lost.

The treatment at 2.5 d AEL with JHm also affected the expression of *Kr-h1*, *Met*, and *myo* (**Fig. 7E**). As expected from their postembryonic relationship in other insects (Jindra *et al*., 2015), exposure to JHm-induced strong *Kr-h1* expression and suppressed *Met* transcripts. For embryonic *myo*, transcript levels are highest (**Fig. 2C**) during the time of peak proliferation as assessed by mitotic activity in the limb buds (**Fig. 7B**). JHm treatment at 2.5d AEL resulted in a small depression of *myo* transcripts at 3.5 d AEL, but severely suppressed transcript levels by 4.5 d AEL (**Fig. 7E**). These effect of early JHm treatment on *myo* expression paralleled its effect on mitotic activity in the limb bud (**Fig. 7B**).

Early treatment with JHm also interrupted the proximal-distal patterning of the limb. Limb bud formation requires the expression of *distal-less* (*dll*) at the tip of the growing bud (Cohen and Jürgens, 1989; Panganiban and Rubenstein, 2002). Up through the entry into katatrepsis, the growing limb buds of JHm-treated and control embryos showed similar expression of Dll (**Fig. 5F**). As leg development progresses, recruitment of additional proximal-distal patterning genes resolves Dll expression into a “sock and band” pattern (*e.g.*, Angelini and Kaufman, 2005; Schaeper *et al*, 2013) as intermediate leg regions become specified. The JHm-treated embryos in **Fig. 7F** were ones that did not complete katatrepsis and they did not further refine their Dll expression. Dll immunostaining was eventually lost and their limbs degenerated. The JHm-treated embryos that completed katatrepsis, by contrast, maintained legs that were shortened but subdivided into coxa, femur, tibia, *etc.* We assume that the latter embryos had progressed far enough through their proximal-distal patterning program before the JHm-induced arrest to produce a stable leg that then maintained its integrity. An earlier arrest of the leg patterning program, however, appears to be insufficient to maintain the limb.

The effects of JHm on cellular differentiation

While early JHm treatment suppressed growth, patterning, and cell determination, it also induced premature cellular differentiation as illustrated by forming muscles (**Fig. 8**). In control embryos (**Fig. 8C**), longitudinal muscle fibers become evident on 4.5 d AEL as thin bands of tissue that

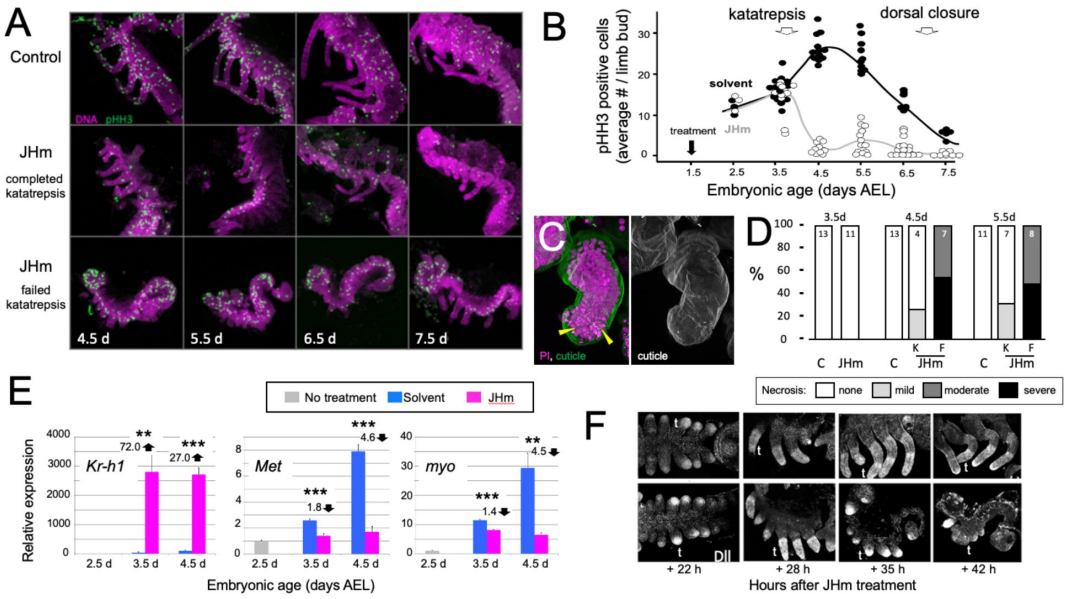

Figure 7.

Effects of early JHm treatment on growth and patterning of the limbs.

(A). Z-stack projections showing the lateral view of embryos that were treated with either cyclohexane (Control) or 1 ng of pyriproxyfen in cyclohexane (JHm) on d1.5 AEL and then dissected and stained on the indicated developmental days. Propidium iodide (PI) (magenta) shows nuclei and anti-phosphohistone H3 (pHH3; green) shows dividing cells. The JHm series follows a subset of embryos that did not undergo katatrepsis (bottom) and a subset that did (middle). **(B).** Summary of the number of pHH3-positive cells in the developing limb buds of JHm and solvent-treated embryos through time. Each dot records the average number of pHH3-positive cells /limb from a single embryo. **(C).** Projected Z-stack through the limb of a JHm-treated embryos that did not undergo katatrepsis. The leg produced a robust cuticle (green; gray scale image) but then started necrosis as illustrated by the highly condensed PI-positive bodies (yellow triangles) in the distal leg. **(D).** The time course of necrosis in the limbs of control and JHm-treated embryos. Necrosis was pronounced in embryos that failed katatrepsis (F) but rather mild in those that completed katatrepsis (K). **(E).** Levels of hormone-related transcripts in embryos treated at 2.5 d AEL with solvent alone (blue bars) or JHm (1 ng pyriproxyfen; pink) and then examined over the following two days. The expression is related to that on the day of treatment (2.5 d; grey) which was set as 1. *Kruppel homolog 1* (*Kr-h1*), *Methoprene tolerant* (*Met*), *myoglianin* (*myo*). Significant differences determined by t-test: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Numbers above columns indicate fold upregulation (upward arrow) or downregulation (downward arrow) relative to cyclohexane control. Each based on three biological replicates. **(F).** Confocal images showing Distal-less (Dll) immunostaining at various times after treatment of embryos at 2 d AEL with solvent (C) or JHm. Embryos are shown from ventral view at 22h post-treatment, and then from lateral view thereafter. t: first thoracic leg.

show weak, uniform staining for actin (as revealed by binding of fluorescent-phalloidin). The growing muscles increase in width over the next two days and their actin staining concentrates at the intersegmental boundaries where the developing muscle fibers attach to tendon cells. The appearance of myofibrils with their repeating sarcomeres becomes evident by 7.5 d AEL, but such embryos, dissected from the eggshells, showed neither spontaneous nor induced movements. By a day later the embryos often showed weak, spontaneous movements when removed from the egg and their muscles have well developed striations (**Fig 8C**, 8.5d). Embryos treated with JHm at 1.5d AEL, by contrast, showed accelerated muscle differentiation (**Fig 8D, E**). These embryos formed myofibrils by 4.5 d AEL regardless of whether or not the embryo completed katatrepsis (**Fig. 8D, E**). Those that completed katatrepsis showed subsequent muscle growth, whereas those that failed katatrepsis showed little further growth.

Early JHm treatment also effected cuticle production. In *Thermobia*, the epicuticle layer of the E1 cuticle is secreted after germ band formation but prior to the start of katatrepsis (**Fig 1**; Konopová and Zrzavý, 2005). A fibrous procuticle is deposited after katatrepsis and covers the embryo through its period of rapid growth and dorsal closure. Chitin staining, using Calcofluor White (Harrington and Hageage, 2003), showed no chitin in the E1 epicuticle (as expected) (**Fig. 9A**, 3.5d AEL), and only faint chitin staining of the procuticle (**Fig. 9A**, 4.5 -7.5 d AEL), indicating that the latter is relatively poor in chitin fibers. Strong chitin staining comes with the deposition of the E2 procuticle on 8.5 d AEL. The latter shows a lamellar ultrastructure (Klag 1978; Konopová and Zrzavý, 2005), which arises from the helical deposition of chitin fibers as seen in typical insect procuticles (Neville, 1965; Vincent, 1980). Like controls, embryos treated with JHm at 1.5 d had no chitin in their E1 epicuticle (**Fig. 9B**, 3.5d AEL) but their E1 procuticle (**Fig 9B**, 4.5 d AEL) showed enhanced chitin staining. These JHm-treated embryos deposited their E2 cuticle at least a day early (**Fig 9B**, 7.5 d AEL).

The JHm-treated embryos depicted in **Fig. 9B** were ones that completed katatrepsis. **Figure 9C** shows a treated embryo that failed to undergo katatrepsis, but it still secreted an E1 cuticle along its ventral surface. This cuticle also had enhanced chitin staining. The chitin-rich E1 cuticle produced in the presence of JHm is more rigid than the normal E1 cuticle. Indeed, control embryos proceeding into katatrepsis are quite delicate and easily disrupted during egg dissections, but JH-treated embryos of the same age are much more resistant to mechanical damage. As discussed below, the rigidity of the modified E1 cuticle may interfere with these embryos undergoing subsequent growth and changes in form.

JHm treatment before deposition of the E2 cuticle also changed the nature of this cuticle. As seen in **Fig. 9D**, the E2 (= J1) cuticle has pebbly surface sculpturing, an egg tooth, and lacks cuticular lenses for its ommatidia. JHm treatment at 4.5 d AEL, though, redirects the epidermis to make a cuticle more like that of the J2 stage. The cuticle lacks the egg tooth and surface pebbling characteristic of the E2 stage but attempts to form J2-like cuticular lenses (**Fig. 9E**). Thus, as in embryos of locusts (Truman and Riddiford, 1999) and crickets (Erezyilmaz *et al.*, 2004), the presence of JH at the outset of the E2 molt causes the embryo to skip ahead to make cuticle characteristic of the next instar.

Overall, then, embryonic development of *Thermobia* becomes sensitive to exogenous JH around the time that the E1 cuticle is being produced. JH treatment suppresses subsequent morphogenesis and cell determination but promotes developmental programs characteristic of the late phases of embryogenesis.

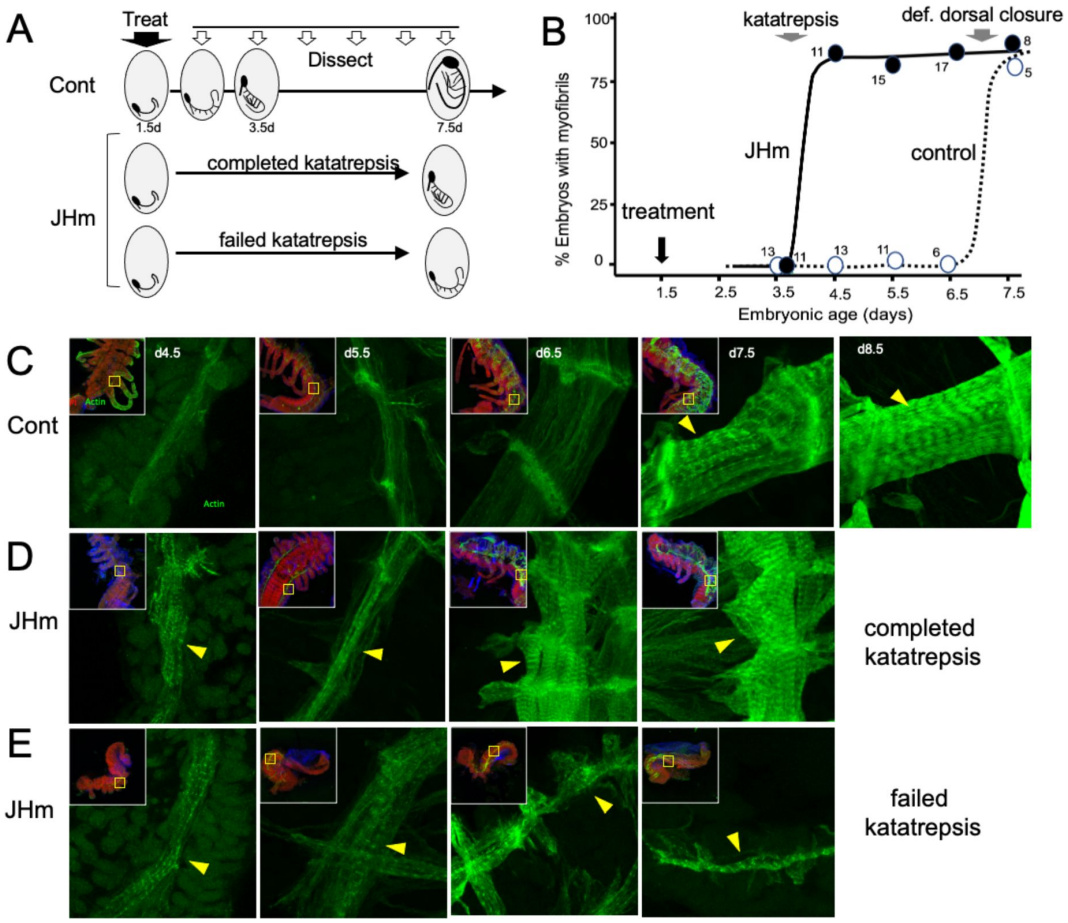

Figure 8.

The effects of JHm in inducing early differentiation of *Thermobia* embryos.

(A). Schematic showing the time of treatment with solvent or 1 ng pyriproxyfen (JHm) at 1.5 d AEL and the subsequent times of dissection and staining of the embryos. **(B)** Quantitation of the effects of JHm treatment on the appearance of striated myofibrils in the developing embryonic muscles. Myofibrils normally appear around the time of definitive dorsal closure, but JHm treatment at 1.5 d AEL advances their appearance by three days. Numbers are embryos examined per point. **(C-E).** Confocal optical sections showing F-actin staining in developing longitudinal muscles of control (C) and JHm-treated (D, E) embryos that were examined at the indicated days AEL. Yellow triangles indicate striations of the myofibrils. Insets show low power views of embryos with the magnified region boxed. green: F-actin shown by phalloidin binding, red: propidium iodide. JHm-treated examples are embryos that underwent katatrepsis (D) and ones that failed to complete katatrepsis (E).

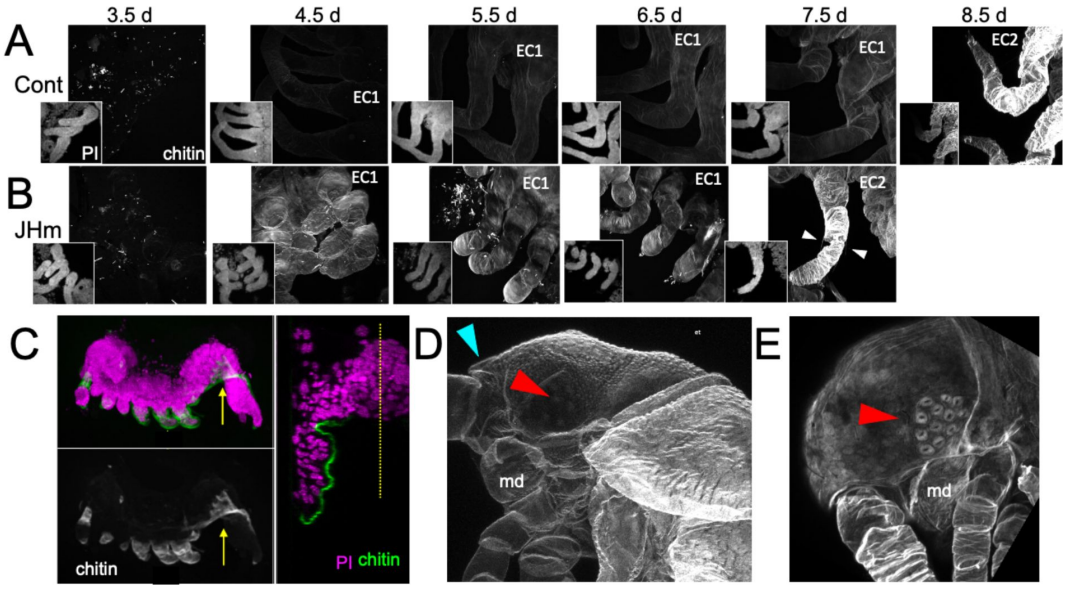

Figure 9.

Effects of 1ng pyriproxyfen (JHm) on the production of E1 and E2 cuticles.

(A, B) Projected confocal Z-stacks of embryos treated with solvent (Control) or JHm at 1.5d AEL and showing chitin staining of the developing legs at various times thereafter. The insets are propidium iodide (PI) staining of the same stack to show the form of the limbs on each day. In both groups no chitin was evident at 3.5d AEL, when only epicuticle is present (dots are due to surface debris). In control embryos, the procuticle of the first embryonic cuticle (EC1) (starting at 4.5 d AEL) stains weakly for chitin, while the second embryonic cuticle (EC2) shows strong chitin staining (8.5d). JHm-treated embryos show enhanced chitin staining of their EC1 and they produce their EC2 a day early as demonstrated by the presence of cuticular hairs (white triangles). All cuticle images were made with the same laser power and gain. **(C)** Lateral view of a 5.5 d embryo that failed to undergo katatrepsis after JHm treatment at 1.5 d AEL . The E1 cuticle covering its ventral surface shows enhanced chitin staining. The arrow shows the plane of the transverse image on the right; the ventromedial region of the embryo is still invaginated into the yolk. PI: propidium iodide staining. Dotted line is the midline. **(D, E)** Projected confocal Z-stacks of 10 d AEL embryos showing the E2 cuticle produced by controls (D) or by embryos treated with JHm at 4.5 d AEL. The cuticle of the control embryo (D) has a pebbly surface sculpturing, an egg tooth (blue triangle) but lacks cuticular eye lenses (red triangle). The JHm-treated embryo produced a cuticle typical of later stages. It is smooth, lacks an egg tooth, and has formed thickened, but abnormal, cuticular lenses (red triangle). md: mandible.

Discussion

The role of JH in embryogenesis of Thermobia domestica

JH appears in *Thermobia* embryos after definitive dorsal closure (**Fig. 2A**). At this point the embryo has completely enclosed the yolk mass and its final size is set. Morphogenetic growth is completed, the E2 cuticle that will be covering the hatchling is being secreted, and developmental programs have shifted to tissue differentiation and terminal maturation. These latter processes are JH dependent (**Fig. 10A**) and do not occur if JH is absent (**Figs. 3**, **4**).

While loss-of-function experiments, which remove JH, produce one type of abnormal development, gain-of-function experiments, involving the providing of JH when it should be absent, produce a different, but complementary, range of abnormalities. As originally reported by Rohdendorf and Sehnal (1973), JHm treatment of *Thermobia* embryos results in a diversity of arrested phenotypes that ranged down to minute embryos that lacked limbs and eyes (as in **Fig. 10B**). The alteration of development by JHm treatment was first evident when the embryo was producing its E1 procuticle. For the developing limb bud, premature exposure to JHm inhibited cell division (**Fig. 7A, B**) and arrested proximal-distal patterning (**Fig. 7F**). If arrest was early enough in the patterning process, the limb bud was not stable and began degeneration despite having deposited a modified E1 cuticle (**Fig. 7C**). The effects of premature JH exposure were well illustrated for the eye (**Fig. 3E**). JH had to be absent during the time when the morphogenetic furrow was moving over the eye primordium (**Fig. 6D-F**). Premature exposure to JHm stopped furrow movement; the cells behind the furrow maintained their determination and made ommatidia cell types, but those in front of the furrow remained undetermined. As summarized in **Figure 6C**, then, many tissues and cell types are determined during the period from the segmented germ band to definitive dorsal closure, and exposure to JHm during this period generated a diversity of phenotypes that reflected the state of embryogenesis when the JHm imposed a morphogenic arrest. Some tissues, like the eye could survive an arrest in early patterning and simply made a small eye (**Fig. 6E**). Other tissues like the leg bud, though, were apparently unstable if patterning was arrested too early and subsequently degenerated.

Importantly, premature exposure to JH does not just simply arrest development. Rather, it shifts cells into programs characteristic of late embryogenesis. Such a shift to later developmental programs by early exposure to JHm is evident in *Thermobia* in the precocious appearance of myofibrils in developing muscle (**Fig. 8D,E**), and in the production of late cuticle types by the epidermis (**Fig. 9B**). Similarly, for eye development in *Schistocerca*, early treatment of embryos with JHm not only arrests the progression of the morphogenic furrow but causes the ommatidia in the wake of the furrow to undergo premature pigment deposition (**Fig. 6 --- figure supplement 1**).

As summarized in **Figure 10A**, *Thermobia* embryos show three distinct phases with regards to JH. The initial **JH-insensitive** phase extends through the formation of the segmented germ band and limb buds. Then follows a **JH-sensitive** phase when the embryo is responsive to JH or JHm treatment. The onset of JH sensitivity correlates with the appearance of Met, and the application of JHm during this period induces transcription of *Kr-h1* (**Fig 7E**), the major JH response gene (Jindra *et al.,* 2015). The appearance of endogenous JH around definitive dorsal closure starts the **JH-dependent** phase. Morphogenetic growth is finished, and JH is required for the terminal differentiation of the determined tissues.

A systemic signal like JH that can switch the embryo from morphogenesis to terminal differentiation may be especially important for short germ band embryos. Eggs may vary in the amount of yolk that they possess (Fox and Czesak, 2000; Yanagi and Tuda, 2012). In such cases

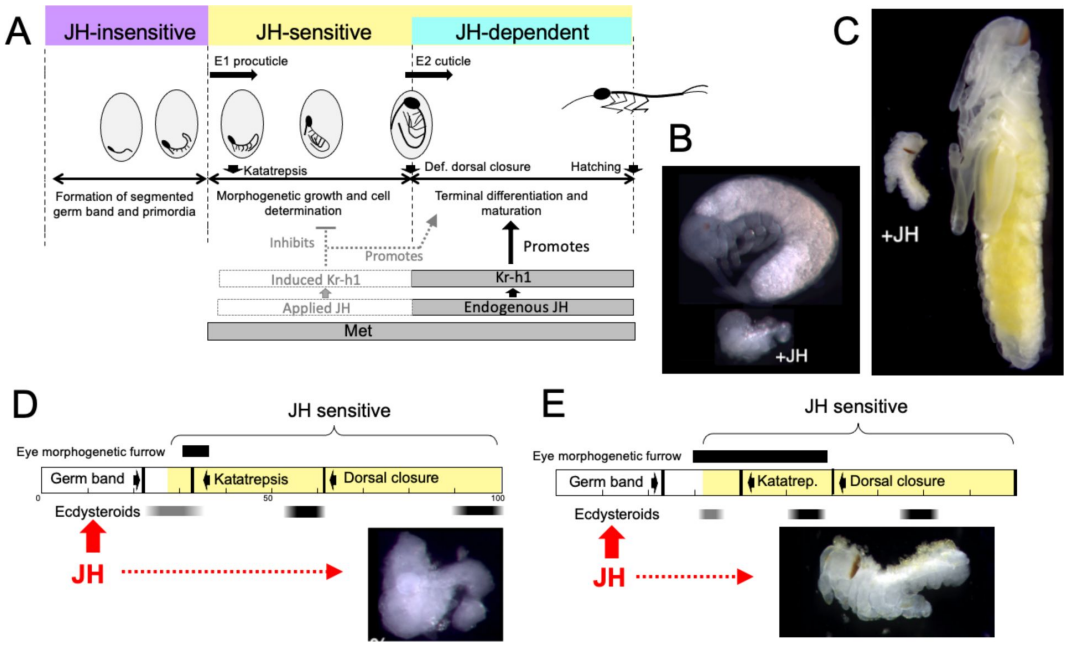

Figure 10

Comparison of responses of short germ band embryos to JH.

(A) Summary of the developmental responses of *Thermobia domestica* embryos to JH. Exogenous JH has little or no developmental effect up through germ band formation. Embryonic development is then altered by JH treatment starting just before deposition of the first embryonic (E1) cuticle, but endogenous JH does not appear until around definitive dorsal closure, when it is needed for terminal differentiation. **(B, C)** Photomicrographs of embryos of *Thermobia* (B) and of *Schistocerca gregaria* (C) comparing the size and morphology of a control embryo at definitive dorsal closure with a clutch mate that had been treated with JHm the day after oviposition (+JH). **(D, E)** Schematic summary of embryonic development of *Thermobia* (D) and *Schistocerca* (E) comparing the time of ecdysteroid surges and the onset of JH sensitivity with the time course of embryogenesis. The black bar shows the time of progressive patterning of the eye primordium. Eye patterning begins **before** *Schistocerca* embryos become sensitive to JH, but **after** *Thermobia* embryos become JH sensitive. Consequently, treatment with JHm (red) a day after oviposition results in *Schistocerca* embryos with tiny eyes but *Thermobia* embryos lack eyes all together. The times of ecdysteroids in the locust are based on data from *Locusta migratoria* (Lagueux *et al*., 1977),

the embryo's maximum size is established once the yolk has been fully internalized at definitive dorsal closure. A systemic signal, like JH, when dorsal closure has occurred might serve to coordinate a shift to terminal differentiation programs across the embryo.

The events responsible for the appearance of Met and of JH sensitivity in the segmented germ band are not known. The fact that the first JH-induced change seen in *Thermobia* embryos is the modification of the E1 molt is interesting considering the intimate relationship between JH and ecdysteroids during the postembryonic molts of hemi- and holometabolous insects (e.g., Riddiford, 1976, 2020). JH acts postembryonically to enforce *status-quo* molts, but there is no *status-quo* to maintain for the first embryonic molt. While the appearance of JH sensitivity coincides with the appearance of *Met* transcripts, the question is still why should the system be sensitive to JH days before the hormone appears? One possibility is that a component of the ecdysone response system is inherently sensitive to JH. An intriguing candidate for such a protein is Taiman. The *taiman* gene encodes a steroid hormone co-activator that mediates ecdysteroid activation (Montell, 2001) and also serves as heterodimeric partner with Met to form the active JH receptor (Jindra *et al.*, 2015; Charles *et al.*, 2011). C-terminal exons of the *taiman* transcript are alternately spliced to form several isoforms in the mosquito, *Aedes aegypti* (Liu et al., 2019), the flour beetle, *Tribolium castaneum*, and the cockroach, *Blattella germanica* (Lozano *et al.*, 2014). JH has been shown to control this splicing in both *Aedes* (Liu *et al.*, 2019) and *Blattella* (Lozano *et al.*, 2014). Interestingly, in mosquito reproduction, the *taiman* isoforms made in the absence of JH poorly support ecdysteroid-induced activation, while those made in the presence of JH mediate strong activation (Liu *et al.*, 2019). We speculate that if a similar relationship were to hold in *Thermobia,* then *taiman* isoforms made in the JH-free environment of the early embryo might support a rather weak ecdysteroid response resulting in the thin, extensible E1 cuticle. JHm exposure, though, would change the *taiman* isoforms perhaps supporting the production of a robust cuticle, more typical of later embryonic molts.

Although early JH exposure affects embryonic growth, tissue patterning, and cuticle types, we do not know how these effects are interrelated. Growth and morphogen signaling interact in complex ways during embryogenesis, with morphogen gradients directing growth, and growth altering morphogen landscapes (Schwank and Basler, 2010; Dekanty and Milan, 2011). Does JH suppress morphogen signaling and this, in turn, suppresses growth or, alternatively, does JH suppress growth which then arrests the progression of morphogen signaling? We find that JH suppresses transcript levels of the TGF-β family member, myoglianin (**Fig. 7E**). In last stage *Drosophila* larvae, this circulating morphogen matches imaginal disc growth with that of the overall animal (Upadhyay *et al.*, 2020). We do not know how it functions in embryos, but it might serve a similar role in short germ band embryos to ensure that limb size is matched to overall embryo size. Whether JH suppression of myoglianin production inhibits embryonic growth or *vice versa* is unknown.

The fact that the rapidly growing embryo is covered by a cuticle presents another complication. The fibrous nature of the E1 cuticle (Konopová and Zrzavý, 2005) likely allows it to stretch to accommodate epidermal proliferation and limb extension. The more robust, E1 cuticle produced after JH treatment (**Fig. 9B**) resists extension and this inextensibility may mechanically hinder subsequent proliferation and growth.

JH also interferes with the morphogenic movements of katatrepsis. These movements can be blocked by JH until shortly before they begin (**Fig. 6C**) and we also find embryos that are blocked in mid-katatrepsis. JH could be inhibiting the contraction of the serosa or its modification of the E1 cuticle may prevent the embryos from passively responding to serosa contractions. We have observed cases in which the extraembryonic membranes have contracted but the miniature embryo has been pulled into the yolk rather than around the outside of the yolk mass (as in **Fig. 5C**). Such cases suggest that a loss of embryo extensibility may be a major factor in the failure of katatrepsis.

Comparative aspects of JH effects on insect embryogenesis

Embryonic JH titers have been measured or estimated for a variety of hemimetabolous and holometabolous insects (see Belles, 2020b). They have been directly determined for embryos of the cockroaches, *Nauphoeta cinerea* (Imboden et al., 1978) and *Blattella germanica* (Maestro *et al.*, 2010), the locust, *Locusta migratoria* (Temin *et al*. 1986), and the moth, *Manduca sexta*, (Bergot *et al.*, 1981b). Alternatively, the abundance of *Kr-h1* transcripts through embryogenesis has been used as a proxy for JH for embryos of the hemipterans *Planococcus kraunhiae,* (Vea et al., 2016) and *Pyrrhocoris apterus* (Konopová *et al.*, 2011), the thrip, *Frankliniella occidentalis* (Minakuchi *et al.*, 2011), the moth *Bombyx mori* (Daimon *et al.*, 2015), and the fruit fly, *Drosophila melanogaster* (Beck *et al.*, 2004). All these insects show an embryonic JH titer like that seen in *Thermobia*: JH appears around definitive dorsal closure when the final size of the embryo has been established.

Consistent with its late appearance, the inhibition of JH production suppresses late embryonic development. Late arrests were seen in *Thermobia* (**Fig. 3**), the stick insect, *Clitumnus extradentatus* (Cavallin and Fournier, 1981), the grasshopper, *Locusta migratoria* (Aboulafia-Baginsky *et al.*,1984), the cockroach *Nauphoeta cinerea* (Brüning *et al.*, 1985) and the milkweed bug, *Oncopeltus fasciatus* (Dorn, 1982). In the latter two cases, late development was restored by treatment with JH or JH mimics. The use of maternal RNAi treatments to knock-down transcripts of components of the JH synthesis and response pathways in *Blattella germanica* (Fernandez-Nicolas and Belles, 2017) also interfered with late embryonic development, although some early embryonic anomalies were also noted. The latter may be related to low levels of maternal transcripts that are loaded into the egg.

Amongst embryos from holometabolous orders, interference with JH production in the beetle *Tribolium castaneum* (Naruse *et al.*, 2020) also resulted in abnormal late development. In *Bombyx*, by contrast, the genetic suppression of JH production caused only a mild delay in terminal embryogenesis but suppressed hatching. When treated larvae are freed from their shells, though, they feed and progressed to the third instar where they then attempted metamorphosis (Daimon *et al.*, 2015). In *Drosophila,* the suppression of JH production had little effect on embryogenesis except causing abnormal migration of the primordial germ cells (Barton *et al.*, 2021). Overall, then, although JH appears during late embryogenesis in all insects, the importance of that JH for the completion of embryogenesis wanes in the holometabolous orders.

Embryos also vary in how they respond to early treatment with JH. The most severely affected embryos are those that undergo short germband development, such as embryos of *Thermobia* (Rohdendorf and Sehnal, 1973; this paper), the locusts, *Schistocerca* and *Locusta* (Novák, 1969; Truman and Riddiford, 1999, 2002) and the cricket *Acheta* (Erezyilmaz et al., 2004). **Figure 10B,C** compares the morphology of normal *Thermobia* and *Schistocerca* embryos at dorsal closure with clutch-mates that were treated with JHm within a day after fertilization. In both cases katatrepsis was blocked and growth was severely retarded. The most severely affected *Thermobia* embryos lacked eyes and their limbs regressed, but the most affected *Schistocerca* embryos possessed small eyes and had stable, although deformed, limbs. We think that these species differences in the severity of JH suppression of embryogenesis are due to changes in the relationship of the embryonic timetable to the timing of ecdysteroid pulses that drive embryonic molts.

The impact of changing the time of embryonic molting relative to the embryogenesis timetable is illustrated for eye development in **Figures 10D, E**. In *Thermobia,* the eye primordium is patterned between about 30 to 45% of development as the morphogenetic furrow moves across it. JH treatment during that period arrests the furrow, thereby determining the size of the eye that subsequently forms (**Fig. 6D, E**). The embryo, though, becomes sensitive to JH suppression when it is depositing the E1 cuticle. Since this time is before the furrow begins to move, the earliest JH treatments prevent furrow initiation and eye development altogether. Eye patterning in locusts,

by contrast, begins at a similar developmental time but extends until dorsal closure to make the large eye of the grasshopper nymph (**Fig 6 ---Supplemental Figure 1**). Ecdysteroids and production of the E1 cuticle occurs relatively later in locusts (Lagueux *et al.*, 1979), though, and the earliest rows of ommatidia have already been determined before the start of the E1 molt and the embryo becoming sensitive to JH. Consequently, JH-treated locust embryos always form an eye, although the size of that eye becomes progressively larger the later the JHm treatment. The difference in the extent of limb suppression in the two species also relates to how far development has progressed at the time that the embryos become responsive to JH: in *Thermobia* the legs are at an earlier stage of proximal-distal patterning as compared to those of *Schistocerca* (Truman and Riddiford, unpublished) and *Acheta* (Erezyilmaz *et al.*, 2004). With the earliest JH treatments, the limbs of *Thermobia* arrest too early to maintain a stable limb, whereas in *Schistocerca* and *Acheta* embryos, leg development has progressed beyond establishing the leg segments of femur, tibia, *etc.*, and although stunted and deformed, the JHm exposed legs are stable.

JH exposure at mid-stage development alters the nature of the E2 cuticle deposited by embryos of *Thermobia* (**Fig. 9**), *Locusta* (Truman and Riddiford, 1999) and *Acheta* (Erezyilmaz *et al.*, 2004). In locusts and crickets, the induced cuticle has the features of the first nymphal (= E3) cuticle, rather than bearing the hatching specializations of the E2 (= Pronymphal) cuticle. Similarly, in *Thermobia,* the E2 (= J1) cuticle produced under the influence of JH has the features of the J2 cuticle and lacks the egg tooth and surface sculpturing that are features of the E2 cuticle (**Fig. 9D, E**). The similarity in the effects of JH on E2 cuticle production in *Thermobia* and in polyneopteron hemimetabolous insects (locusts and crickets) suggests that their last common ancestor would have responded to JH exposure in a similar way. Hence, the ancestral effects of JH on molting were in evoking **progressive** molts to the final juvenile condition. The function of JH in maintaining ***status quo*** molts came later, when this hormone began being used during postembryonic molts.

Insects that show intermediate germ band development such as the linden bug, *Pyrrhocoris apterus*, devote more of the blastoderm to the production of the germband than do the short germband forms (Anderson, 1972a). Premature exposure to JH also suppresses katatrepsis and dorsal closure but their growth suppression is not as severe as seen in the above species (Enslee and Riddiford, 1977), likely because the embryos are relatively larger when they become responsive to JH. JHm treatment also causes an advancement in embryo pigmentation (Enslee and Riddiford, 1977).

Embryos of holometabolous insects typically show either intermediate or long germband development (Anderson, 1972b) and they are the least affected by exposure to exogenous JH. These embryos form their germband in its “appropriate” position with its head directed to the anterior pole of the egg and, hence, does not show the movements of katatrepsis (Anderson, 1972b). The elongated embryos of the Lepidoptera, though, show an unrelated set of movements around dorsal closure (Hemming, 2003; Anderson, 1972b) to reposition the embryo so that its dorsal surface is against the shell. These embryos enclose only part of the yolk at dorsal closure and subsequently consume the remainder of the yolk before hatching. JH treatment to embryos of the giant silk moth, *Hyalophora cecropia,* and the sphinx moth, *Manduca sexta* (Riddiford and Williams, 1967; L.M.Riddiford, unpublished) blocks the repositioning of the embryo and its ventral surface remains against the shell. Although there is physical distortion caused by their ventral-out position, these embryos finish their development in a relatively normal manner. These embryos, though, can neither consume the extraembryonic yolk nor hatch.

Long germband embryos, as seen in Diptera and Hymenoptera, are least affected by JHm treatment. As best characterized in *Drosophila* (Cohen, 1993), almost all the blastoderm is devoted to making the germband, and the body axis is established simultaneously along its length, with organ primordia established soon thereafter. Compared to their development in short germband embryos, the embryonic primordia for structures like the eyes (Friedrich, 2006) and

legs (Tanaka and Truman, 2007) only undergo early phases of their patterning, with the patterned portion forming the larval structure, and the remainder set aside as a diploid primordium. In the epidermis of *Drosophila,* most of these persisting embryonic primordia are sequestered as invaginated imaginal discs and contribute nothing to the larval body. In species with less derived development, the imaginal primordia are embedded within the larval epidermis and help in making the larval structure. Compared to their short germband relatives, the primordia of long germband embryos show relatively little proliferative growth after they are established. This de-emphasis on proliferative growth removes the feature that was most sensitive to JH suppression in short germband embryos. Of course, as covered in the next section, this phase of proliferative morphogenesis has been translocated from the embryo to the last larval instar in holometabolous insects and its JH sensitivity may have been carried with it.

Relevance of the embryonic effects of JH in Thermobia to its postembryonic effects in hemimetabolous and holometabolous insects

Although insects show similar titers of JH during embryogenesis, they differ in their pattern of JH production during postembryonic life (**Fig. 11A**). The only information for ametabolous insects is for *Thermobia domestica.* Direct hormone measurements (**Fig. 2A**), and *Kr-h1* transcript levels (Fernandez-Nicolas *et al.*, 2023) indicate that JH levels are low at hatching and remain low throughout juvenile growth and into the adult. In hemimetabolous insects, by contrast, JH titer measurements or *Kr-h1* expression data are available for examples of paleopteran (mayflies; Kamsoi *et al.*, 2021), polyneopteran (including grasshoppers and cockroaches: Temin *et al.*, 1986; Lanzrein *et al.*, 1985; Maestro, *et al.*, 2010) and paraneopteran orders (heteropteran, Konopová *et al.*, 2011). High levels of JH are present through the penultimate nymphal instar but then disappear in the last nymphal stage. This decline in JH is both necessary and sufficient for metamorphosis to the adult. In the Holometabola, JH levels are high through the penultimate larval stage but then decline early in the last larval stage, as the larva becomes committed to metamorphosis. After pupal commitment, JH transiently returns during the prepupal period. This reappearance of JH is needed by some tissues to prevent their premature “jump” to the adult stage (Williams, 1961). JH must then be cleared from the system to allow the transition of the pupa into the adult.

As discussed above, the similarity of the effects of JH in embryos of *Thermobia* and of polyneopteran hemimetabolous insects argue that JH also had the ability to suppress morphogenesis and promote terminal differentiation in the last common ancestor before these groups diverged about 400 mya. How, then, do these ancestral, embryonic actions of JH relate to its modern function of regulating metamorphosis, and what were the selective pressures that moved JH into the postembryonic realm?

The embryonic actions of JH are compared with its postembryonic actions in **Fig. 12**. In the ancestral condition, JH can act in the embryo to suppress morphogenesis and promote differentiation, but, since it normally appears after morphogenesis and tissue patterning are complete, its main embryonic function is to support terminal differentiation. In *Thermobia,* JH levels are then quite low in the juvenile (**Fig. 2A**; Fernandez-Nicolas *et al.*, 2023), indicating that JH is not needed to maintain the juvenile form. Watson (1967) showed that the appearance of scales in its J4 stage is suppressed by JH application, but we have not been able to induce premature scale formation in the J3 stage by treatment of the J1 and J2 stages with 7EP (Truman and Riddiford, unpublished). We do not think that the appearance of scales is **caused** by a modulation in the low postembryonic JH levels. Rather, the ability of JH to suppress scale morphogenesis in the juvenile is likely an extension of its morphostatic actions that were evident in the embryo.

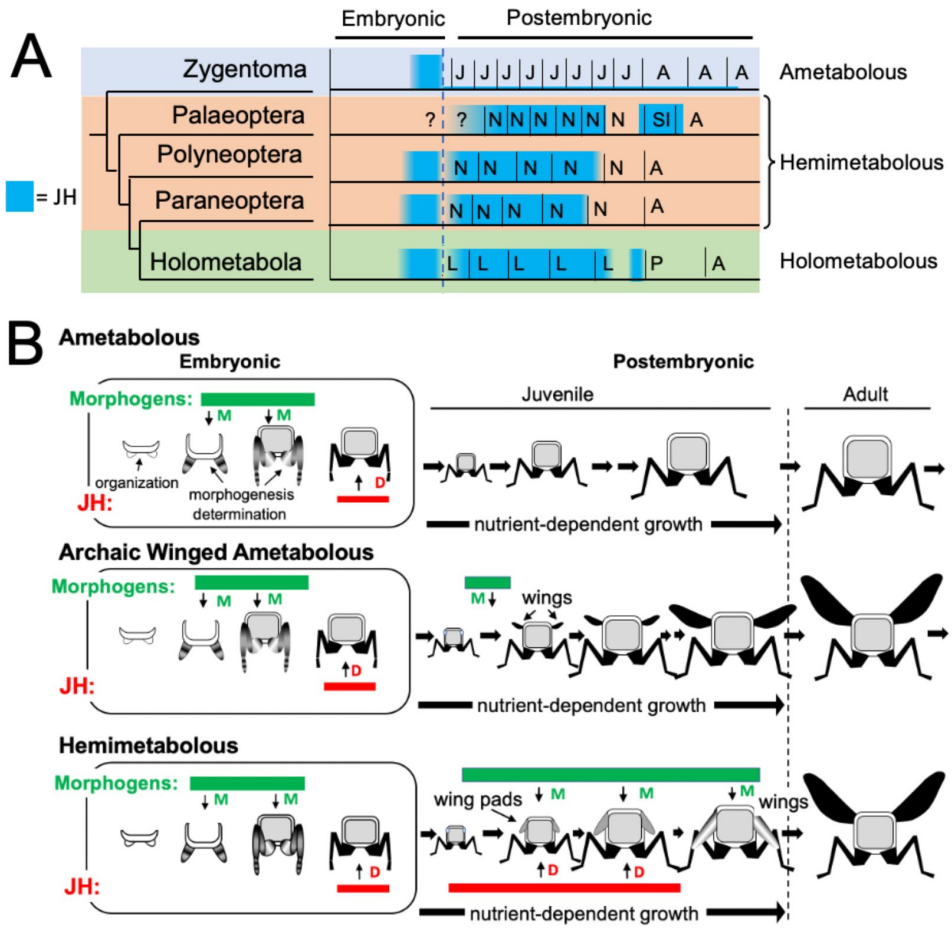

Figure 11.

Phylogenetic shifts in JH production during embryonic and postembryonic development in insects.

(A) Depiction of JH titers in ametabolous, hemimetabolous, and holometabolous insects. Titers are based on direct measurements or are estimated from *Kr-h1* expression. The ametabolous order, Zygentoma, provides the only data for an ametabolous insect, *Thermobia* (**Fig. 2A**; Fernandez-Nicolas *et al*., 2023). Palaeopteran postembryonic data from the mayfly, *Cloeon dipterum* (Kamsoi *et al.,* 2021). Polyneopteran titers based on locusts (Temin *et al.,* 1986; Truman and Riddiford, 1999) and *Blattella* (Maestro *et al.,* 2010). Paraneopteran from *Pyrrhocoris* (Konopova *et al*. 2011) and Holometabolous for *Manduca* (Bergot *et al.,* 1981b; Baker et al., 1987; Fain and Riddiford, 1975). **(B)** A scenario for the role of postembryonic JH in the evolution of the wing pad. In the ametabolous condition, as typified by *Thermobia*, the major phase of body morphogenesis (M) is confined to mid-embryogenesis, followed by the appearance of JH which supports differentiation (D). In archaic winged insects a new, postembryonic phase of morphogenesis supports wing formation in the young juvenile. The small wings then undergo positive allometric growth until they are large enough to support flight of the older juveniles and the adults. The postembryonic, reappearance of JH during wing morphogenesis redirected development to make the wing pad. This compromise developmental program is then maintained until the end of juvenile growth when the disappearance of JH allows wing differentiation.

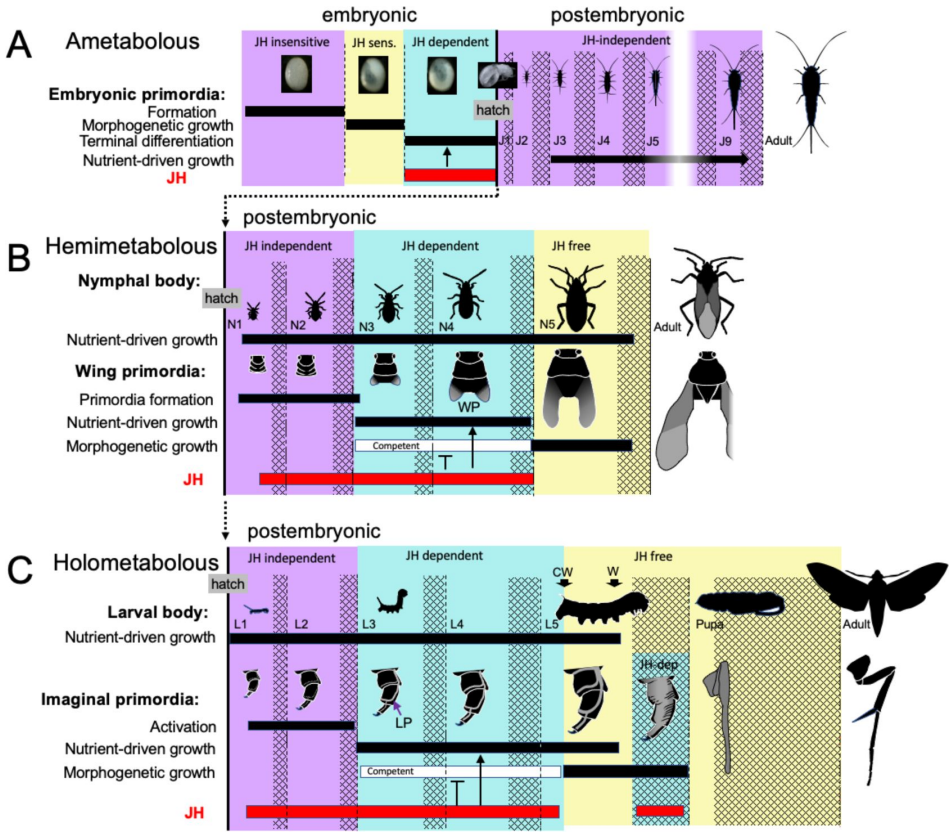

Figure 12.

Comparison of the developmental effects of JH in *Thermobia* with its postembryonic actions in hemimetabolous and holometabolous insects.

(A) As summarized in **Figure 10**, early *Thermobia* embryogenesis is JH insensitive, but JH sensitivity is acquired just prior to katatrepsis and the production of the first embryonic cuticle. JH appears after definitive dorsal closure and is required for the terminal differentiation of the juvenile. Once the juvenile form is established, JH is not then needed for its maintenance. **(B)** The early nymphal instars of hemimetabolous insects are also JH independent. Morphogenesis, associated with wing development, begins around the third nymphal stage and is correlated with the appearance of JH dependence. JH allows wing pad (WP) growth but suppresses its morphogenesis until the disappearance of JH ushers in the JH-free period which allows wing morphogenesis and differentiation. **(C).** The function of JH in holometabolous larvae is like that seen in nymphs except that imaginal primordia (like the leg primordia [LP]) are widely spread through the larval body and involve almost all of the adult organs. The imaginal primordia and the larval cells differ in their JH requirements during the prepupal period (see text). The pupal-adult transition then requires the absence of JH. CW: critical weight checkpoint; W: wandering stage; double crosshatch: period of new cuticle production preceding each ecdysis.

Unlike the juveniles of *Thermobia*, the nymphs and larvae of hemi- and holometabolous insects have long been known to need JH to maintain their respective states. However, more recent studies involving the loss of JH or JH function in the silkworm, *Bombyx mori* (Daimon et al., 2015), and the bug *Pyrrhocoris apterus* (Smykal *et al.*, 2014) show that the early juvenile instars are maintained regardless of the presence or absence of JH or its main effector, Kr-h1. The juveniles shift from a JH-independent to a JH-dependent state around their 3rd instar. After this point, JH is needed to suppress their entry into metamorphosis (e.g., Smykal *et al.*, 2014; Chafino *et al.*, 2019). Although likely associated with growth (Smykal *et al.*, 2014), the factors that cause metamorphic competence are unknown.

Nymphs and larvae differ from juveniles of *Thermobia* in that they have a second round of morphogenesis during their postembryonic growth (**Fig. 12B, C**). However, the primordia that undergo postembryonic morphogenesis are typically dormant at hatching and need a period of growth before they start developing. In true bugs, like *Pyrrhocoris*, for example, wing pads only appear at the start of the 3rd nymphal stage (Smykal *et al.*, 2014). Likewise in holometabolous larvae, such as the butterfly, *Pieris rapae*, cells of the wing primordia are evident at hatching but are still attached to larval cuticle. As the larva feeds and grows, the cells of the primordium increase in size, detach from the cuticle, form an invaginated sac, and finally start dividing during the molt to the third larval stage (Mercer, 1900; see review in Svacha, 1992). How growth may cause the activation of dormant primordia has been examined for the eye-antenna (Kenyon *et al.*, 2003) and the wing-notum discs (Rafel and Milan, 2008) of *Drosophila.* These discs are dormant at hatching because of opposing actions of short-range morphogens at the two edges of their respective discs. The inhibition imposed by these morphogens prevents the subsequent regionalization of these discs into eye *versus* antenna and wing *versus* notum domains, respectively. As the hatchling feeds and grows, the increase in disc cell size eventually moves the edges of the discs out of the zone of inhibition, thereby allowing the start of cell division and patterning (Kenyon *et al.*, 2003; Rafel and Milan, 2008). Similar growth dependent changes in local morphogen signaling likely also control the initiation of wing pad formation in hemimetabolous nymphs. Whether the developing wing pads and other imaginal primordia are sources of the competence signals, though, is not known. However, once these tissues acquire metamorphic competence, JH is needed to delay its realization until nymphal/larval growth is over (Smykal *et al.*, 2014).

The appearance of high levels of JH during postembryonic life likely occurred after the invention of wings and powered flight (**Fig. 10B**). Fossil series of juvenile archaic flying insects, such as the Megasecoptera, show that the thorax of young juveniles bore small, articulated wings, although the latter were too small for flight (Kukalova-Peck, 1978; Haug *et al.*, 2016). Through successive instars, the small wings showed positive allometric growth until they became large enough to support flight in the late juvenile and the adult stages. These insects, though, were still considered ametabolous because there was not an abrupt morphological change going from the juvenile to the adult (Kukalová-Peck, 1978). Wing development was subsequently modified so wing primordia appeared as immobile wing pads appressed to the body rather than as lateral, moveable winglets. As a wing pad, developing tissues were protected during juvenile growth and they deferred their morphogenesis and differentiation until juvenile growth was finished. This wing pad is a feature of all extant hemimetabolous insects.

We assume that, like *Thermobia*, the ametabolous archaic winged insects produced little or no JH through juvenile life (**Fig. 11B**). The change to making a wing pad, rather than a wing, may have occurred by bringing JH into the postembryonic realm at the time when wing morphogenesis was starting. While agents that drive morphogenesis and differentiation were separated in time during embryogenesis, their co-occurrence during wing formation may have forced a developmental compromise. The influence of local morphogens on the wing pad is evident in their cells remaining diploid, undergoing progressive patterning, and showing positive allometric growth, but under the influence of JH the wing pad cells remain undetermined, they make nymphal

cuticle, and their growth depends on nutrient input. In modern insects, this compromise condition lasts while JH is present, and if JH or its effector Kr-h1 are removed, then the wing pad rapidly undergoes morphogenesis and differentiation into a wing (*e.g.* Konopová *et al.*, 2011). Once wing pad development established the need for JH in the postembryonic domain, this hormone was likely adopted by other systems, such as those regulating cuticle type, to control other phenotypic differences between the nymph and the adult.

Holometabolous larvae similarly use JH to suppress wing morphogenesis during larval growth (**Fig 12C**), but, in addition, they have scattered imaginal primordia that are embedded in larval organs or are early invaginated discs. The morphogenesis of these imaginal primordia is also suppressed by JH. When JH finally disappears at the critical weight checkpoint (Nijhout and Williams, 1974; Nijhout, 1994), the primordia embark on their program of morphogenetic growth that is independent of nutrient input (Truman *et al.*, 2006).

The transformation of the larva into the adult requires two molts, with the nonfeeding pupal stage interposed in between. In terms of their JH requirements, the transition from the pupa to the adult is like that from the last stage nymph to the adult. They both occur in a JH-free environment, and exposure to JH at the outset of the molt redirects development to make another pupal or nymphal stage, respectively. The transition from the larva to the pupa, though, is unusual in that JH returns during the prepupal period (**Fig. 11A**). As depicted in **Figure 12C**, this JH is especially important for the tissues that come from the imaginal primordia. For regular larval tissues, the commitment from the larval program to the pupal program is caused by the small ecdysteroid peak that evokes wandering and, thereafter, JH cannot stop their pupal differentiation (Riddiford, 1976). The imaginal primordia, by contrast, have an earlier commitment to pupal differentiation at the critical weight checkpoint. In a species- and tissue-specific fashion, these imaginal primordia may fail to undergo normal pupal differentiation if JH is absent during the prepupal period (Williams, 1961; Kiguchi and Riddiford, 1978; Riddiford *et al.*, 2010). This requirement of some imaginal primordia for JH for their proper pupal differentiation is reminiscent of the requirement by embryonic primordia of basal insects for JH to complete their nymphal differentiation. It is important, though, that the outcome of the lack of JH differs in the two cases: its lack in the embryo results in suppression of juvenile/nymphal differentiation whereas its lack in the prepupa results in an “overshoot” to the adult stage. We do not know enough about either of these phenomena, though, to reconcile these differences.

The above discussion proposes an inherent antagonism between JH and morphogen signaling. This antagonism has been assumed based on phenotypic effects such as JH stopping eye primordium patterning in embryos (**Fig. 6 – figure supplement 1**) or in premetamorphic larvae (Nijhout and Kremen, 1998;). To date, though, the only morphogen that has been directly tied to JH is the circulating morphogen, myoglianin. A major source of myoglianin in larvae is muscle and it provides a proxy for body size, to inform the insects that sufficient growth has occurred to permit metamorphosis (He *et al.*, 2020). Studies on the cricket, *Gryllus bimaculatus* (Ishimaru *et al.*, 2016) and on *Blattella* (Kamsoi and Belles, 2019) show that myoglianin acts on the corpora allata to suppress JH production, thereby allowing imaginal primordia to switch to morphogenetic growth. Late in larval life in *Drosophila*, systemic myoglianin also provides information to coordinate imaginal disc growth to overall body size (Upadhyay *et al.*, 2020). In *Thermobia* embryos, we find that levels of JH and myoglianin are also related, but the relationship is reversed, with myoglianin appearing first, during the period of morphogenetic growth, and early application of JH able to suppress this appearance. We have no experimental data on the function of myoglianin in *Thermobia* embryos, but in a short germband insect where yolk content might be variable, it may be important to have a circulating morphogen to match appendage size to body size. Although the inhibitory relationships between myoglianin and JH are in opposite directions in the embryo versus in the juvenile, an interaction of the two signaling systems appears to extend deep into insect evolution.

Conclusions

The ancestral developmental role for JH appears to have been in the embryo where it functioned to promote terminal tissue differentiation. JH also had powerful morphostatic activity, but this activity was not evident during normal development because JH appeared late in embryogenesis after morphogenesis had essentially finished. These embryonic actions of JH, though, preadapted it to become the consummate *status quo* hormone in the postembryonic realm. Once *Thermobia* embryos have hatched, they do not need JH to maintain their juvenile condition. The same is true of nymphs and larvae **until** around the time that dormant primordia initiate their morphogenetic growth. Once these primordia acquire competent to begin programs of morphogenesis, the morphostatic actions of JH maintain them in an immature condition. The removal of JH is needed for these primordia to achieve their developmental potential.

JH signaling and action extend back into the Crustacea where its immediate precursor, methyl farnesoate (MF), is involved in reproductive control (Borst *et al.*, 1987). MF also affects crustacean development, but these effects are subtle and diverse (Laufer and Biggers, 2001) and difficult to compare with JH effects in *Thermobia* at this time. An involvement of farnesol derivatives in growth and differentiation may extend beyond the pancrustacea. In the yeast *Candida albicans*, secreted farnesoic acid acts as a "quorum sensing signal" that controls the transition from a budding form to a hyphal form (Hornby *et al.*, 2001; Oh *et al.*, 2001). Amongst animals, the genes for the enzymes to synthesize farnesoic acid are widely found throughout invertebrate phyla (So *et al.*, (2022). In mammals, farnesol stimulates differentiation in epidermal keratinocytes (Hanley *et al.*, 2000) and it also suppresses xenograft-based tumor growth in mice (Lee *et al.*, 2015). Indeed, farnesol-based molecules may have an ancient involvement in switching cells between developmental states and this capacity may have been exploited by the insects to provide the hormonal system that regulates their metamorphosis.

Methods

Information on specialized reagents is summarized in **Table 1**.

Animals

The firebrats, *Thermobia domestica*, were reared at 37°C in small, covered polyethylene boxes. Layers of corrugated filter paper provided surfaces for the insects to move on and hide. The insects were fed dry Gerber's baby rice cereal and a few pellets of dry cat food. Water was available in cotton-plugged vials. The incubator was kept above 70% relative humidity with a saturated KCl solution.

Cotton balls were placed between the filter paper sheets for oviposition. For timed egg collections, the cotton balls were replaced morning and evening to achieve 12-hour egg collections, and each was stored in a covered petri dish at 37°C until needed. The age of the embryos was referenced to the midpoint of the collection period.

Juvenile Hormone Titers

Timed egg collections were extracted based on the method of Bergot *et al.* (1981a) as modified by Lacy Barton and Justina Sanny (personal communication) and by LMR. Briefly, 200 eggs were homogenized in 350 µl acetonitrile containing 31.25 pg deuterated JH III (JHD3) in a silanized 2 ml Snap-It vial (Thermo-Fisher) on ice using a Benchmark D1000 homogenizer (Benchmark Scientific, New York), then capped and spun at 5000 g for 15 min at 4°C. The supernatant was transferred to a new silanized vial. The pellet was resuspended in 250 µl acetonitrile containing 31.25 pg JHD3 III, spun at 5000g for 15 min, then the two supernatants combined. The combined supernatants were

Reagent / animal	Source	Catalog number
Thermobia domestica	30+ year laboratory colony	est. from wild caught
pyriproxyfen	Sumitomo Co	#95737-68-1
7 ethoxyprecocene	Sigma Aldrich	#65383-73-5
DAPI	Sigma Aldrich	#28718-90-3
Calcofluor White	Sigma Aldrich	#4193-55-9
Propidium Iodide	Thermo Fisher Scientific	#440301000
Oregon Green phalloidin	Thermo Fisher Scientific	#O7466
rabbit anti-distal-less	gift from Grace Panganiban	
rabbit anti P-HistoneH3 (ser 10)	EDM Millipore	#06-570
Normal Donkey Serum	Jackson ImmunoResearch	#017-000-121
AF488 Donkey anti-rabbit IgG	Jackson ImmunoResearch	#711-545-152
AF594 Donkey anti-rabbit IgG	Jackson ImmunoResearch	#711-585-152
DPX mountant	Electron Microscopy Sciences	# 13512

Table 1.

Specialized animals and reagents

extracted with two volumes n-pentane and 4 volumes of 4% NaCl, then spun at 2000 g for 20 min at 4°C. The organic phases and aqueous phase were put into separate silanized vials, and the aqueous phase re-extracted with a half volume of n-pentane and spun 20 min at 4°C. The resultant organic phase was combined with the original organic phases which was then washed with an equal volume of 4% NaCl, and centrifuged at 2000 g for 20 min at 4°C. The organic phase was then transferred to a new silanized vial, the solvent gently blown off under a stream of nitrogen, and the residue resuspended in 200 µl acetonitrile. The residue and two 150 µl rinses of the vial were loaded onto a Sep-Pak C18 column (3cc; Waters Corp., Milford, MA, USA). The purified extract was eluted from the column with 2 ml acetonitrile and frozen at -20°C until analysis by the liquid chromatography-tandem mass spectrometry method of Ramirez *et al*. (2020).

Ecdysteroid titers

Ecdysteroid concentrations in timed egg collections were measured using the 20-Hydroxyecdysone (20E) Enzyme Immunoassay (EIA) kit (Cayman Chemical Company, Ann Arbor, MI) based on the method developed by Porcheron *et al*. (1989). Staged *Thermobia* embryos (200 per sample) were homogenized in 250 µls ice cold 75% aqueous methanol as outlined in Margam *et al*. (2006). Homogenized samples were centrifuged for 15 minutes at 13,000g and 4°C. Supernatants were transferred to 1.5 ml microcentrifuge tubes on ice. Pellets were resuspended in 250 µls 75% aqueous methanol, vortexed, placed on ice for 30 mins, then centrifuged as before, and the supernatants pooled. One quarter of the volume was dried down under nitrogen, stored desiccated at -20°C. It was resuspended in EIA buffer and diluted 1/100 just before assay. Following the kit instructions, the EIA was performed in a 96-well microtiter plate and is based on the competition between 20E (in standard or sample) and acetylcholinesterase-labeled 20E for the ecdysteroid antiserum that has been bound to the IGG-coated well plates. The plate was incubated with gyration overnight at 4°C, then washed five times with EIA buffer. The enzymatic substrate for acetylcholinesterase and chromogen, which form a yellow compound that absorbs between 405-414 nm, was then added to each well and incubated at room temperature with gyration for 60 min. The intensity of the color is inversely proportional to the amount of ecdysteroid present as determined by spectrophotometry on a µQuant Microplate Spectrophotometer plate reader at 410 nm (BioTek Instruments, Vermont). The kit solutions were resuspended in UltraPure water (Cayman Chemical). The readings were compared to a standard curve derived from serial dilutions of the 20E standard and quality control provided by the kit.

Bioactive compounds

Pyriproxyfen (Sumitomo Co.) and 7-ethoxyprecocene (Sigma Aldrich) were dissolved in cyclohexane (HPLC grade, Sigma Aldrich) and stored at -20°C. Using a 10 µl Hamilton syringe, 0.2 µl of hormone solution or of cyclohexane was applied with a repeating dispenser to staged eggs on double-stick tape.

RNA analysis

Collections of timed embryos were placed in a 0.5 ml Eppendorf tube to which 150 µl Trizol (Ambion) was added. The tube was vortexed, briefly spun, then frozen in liquid nitrogen. Total RNA was isolated using TRIzol (Invitrogen), treated with TURBO DNase (Invitrogen) and purified with RNA Clean & Concentrator (Zymo Research). cDNA was prepared from 2 µg of the RNA using oligo-dT primer and SuperScript IV First-Strand Synthesis System (Invitrogen). PCR was performed using SsoAdvanced Universal SYBR Green Supermix (Bio-Rad); each 20 µl reaction contained 100 ng cDNA and forward and reverse primers, each primer at a final concentration of 500 nM. Reactions were run in the CFX Connect Real-Time PCR Detection System (Bio-Rad) and normalized expression was calculated using the associated software according to comparative Ct method (Schmittgen and Livak, 2008). The expression levels of each target gene were normalized against expression levels of the ribosomal protein 49 (rp49). Primers were designed using Primer3Plus (Untergasser *et al*. 2012) on the gene sequences that were derived from NCBI: Met and Kr-h1

were isolated by BK previously (Konopová et al. 2011), myo was found in the TSA database by blast search using Drosophila myo as a query and the amplicon sequence was also checked in the Thermobia genome (Brand *et al*. 2018) to check for nucleotide mismatches (sites of polymorphism). The accession numbers and primer sequences are in **Table 2**. Melting curves were examined after each run and for each pair of primers several finished runs were visualized on a 2% agarose gel; only a single product was detected.

On selected samples including young embryos, old embryos, and juveniles we checked which of the possible reference genes would give the most consistent expression levels: we tested rp49 (also known as Ribosome protein L32), Elongation factor-1α, Actin 5C (Ω-actin), α− Tub84B (α-tubulin). rp49 appeared most suitable. This choice agrees with other studies in *Thermobia* (Bai et al. 2020, Fernandez-Nicolas et al. 2023).

Immunocytochemistry

Embryos were dissected and fixed in 3.9% formaldehyde (Thermo Fisher Scientific) in phosphate-buffered saline (PBS; Fisher Scientific) for 30 to 60 min, then rinsed three times in PBS with1% Triton X100 (PBS-TX; Fisher Scientific). They were then incubated with agitation in PBS-TX with various combinations of stains for 1-2 days at 4°C. Tissue stains were propidium iodide (Thermo Fisher Scientific, 1:1000 dilution of 1 mg/ml stock) or DAPI (Thermo Fisher Scientific, 1:1000 dilution of 1 mg/ml stock) for DNA, Alexa-488 conjugated phalloidin (Thermo Fisher Scientific, 1:100 dilution of 200 units/ml stock in methanol) for actin, and Calcofluor White (Sigma Chemical) for cuticle. Stained tissues were repeatedly rinsed, mounted on poly-L-lysine (Sigma-Aldrich) coated coverslips, dehydrated through a graded ethanol series, cleared through three changes of xylene, and mounted in DPX (Sigma-Aldrich).

A rabbit antibody against phosphohistone H3 (#06-570: anti phosphor-Histone H3 (ser 10); EDM Millipore, Darmstadt, Germany) was used at a 1:1000 dilution to identify mitotic cells. Tissue was preblocked in 2% normal donkey serum (Jackson Immunoresearch Laboratories, West Grove, PA, USA) for 15 to 30 min, then incubated with the primary antibody over two to three nights. Following five to six rinses in PBS-TX, tissues were incubated with a secondary antibody along with a variety of stains. Secondary antibodies were various Alexa Fluor 488-, 594-, or 647-conjugated donkey antisera raised against rabbit IgG fractions and used at 1:500 (Jackson Immunoresearch Laboratories, West Grove, PA, USA). Selection of the secondary depended on the combination of stains that were used. After staining, tissues were mounted, dehydrated, cleared and mounted as described above. The preparations were imaged on a Zeiss 800 confocal microscope and processed with ImageJ software (*http://imagej.nih.gov/ij/*).

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Source Data Tables

Figure 1 source data 1. The percent of embryos attaining a particular developmental “milestone” as a function of the time after egg laying at 37°C. Age of each sample calculated from the midpoint of its 12 hr egg collection.

gene	sequence accession number (NCBI)	forward primer (5'-3')	reverse primer (5'-3')
Met	JN416986.1	TACTCCATCCACACAGTCAAGG	TTCCGTGATTCGACGATCTCTC
Kr-h1	JN416989.1	ACTCCGTCGAATGGTACTAGTG	GTTCTTGCATGGGAGGAAACTG
myo	GASN02042720.1	TTCAACAAGCAAGCCCACAAG	ACACCGATCCACTACCATTCC
rp49	AB689035.1	CTAAAGAGGAACTGGCGCAAAC	GTTTAGTCTTCTTGGCGCTTCC

Table 2.

Primers used for real-time PCR.

Embryonic age hrs (days)	N	germ band	extended limbs	post katatrepsis	eye pigmentation	dorsal closure	shed EC1	resorb EEF	hatch
50 h (2D)	23	65%	0						
62 h (2.5D)	23	100%	0						
74 h (3D)	24	100%	79%	0					
84h (3.5D)	25	100%	100%	0					
96 h (4D)	33	100%	100%	76%	0				
108 h (4.5D)	28	100%	100%	100%	0				
121 h (5 D)	24	100%	100%	100%	8%				
133 h (5.5 D)	23	100%	100%	100%	48%				
145 h (6 D)	23	100%	100%	100%	95%	0			
157 h (6.5 D)	38	100%	100%	100%	100%	0			
169 h (7 D)	30	100%	100%	100%	100%	10%	0		
180 h (7.5D)	48	100%	100%	100%	100%	77%	ND	0	
192 h (8 D)	37	100%	100%	100%	98%	98%	71%	3%	
204 h (8.5 D)	26	100%	100%	100%	100%	100%	85%	15%	
216 h (9 D)	41	100%	100%	100%	100%	100%	95%	78%	0
229 h (9.5 D)	28	100%	100%	100%	100%	100%	100%	96%	0
241 h (10 D)	50	100%	100%	100%	100%	100%	100%	100%	0
253 h (10.5 D)	50	100%	100%	100%	100%	100%	100%	100%	10
265 h (11 D)	50	100%	100%	100%	100%	100%	100%	100%	94%
277 h (11.5 D)	50	100%	100%	100%	100%	100%	100%	100%	100%

Figure 2 supporting data 1. Age of samples extracted for Juvenile Hormone III measurements. Age of samples from midpoint of 12 hr egg collections. E: embryonic age; J: age of juvenile; n.d.: below range of detectability.

Sample	Age at extraction	individuals extracted	pg/ml	fmol	Fmole JH III/ individual
001	E_5d 9h	196	n.d.	0	0
002	E_5d 9h	203	n.d.	0	0
003	E_5d 9h	205	n.d.	0	0
004	E_5d 9h	208	n.d.	0	0
005	E_6d 10h	202	97	54	0.5
006	E_6d 10h	212	5474	3082	14.5
007	E_6d 10h	191	265	149	0.8
008	E_7d 10h	205	265	149	0.7
009	E_7d 10h	134	119	67	0.5
010	E_7d 9hr	120	73	41	0.3
011	E_8d 9h	202	957	539	2.7
012	E_8d 9h	198	912	514	2.6
013	E_8d 9h	171	802	451	2.6
014	E_9d 9hr	198	1748	984	5
015	E_9d 9hr	192	1102	621	3.2
016	E_9d 9hr	199	1946	1096	5.5
017	E_10d 9h	204	4403	2480	12.2
018	E_10d 9h	201	15864	8933	44.4
019	E_10d 9h	201	21158	11914	59.3
020	E_11d 9h	191	10874	6123	32.1
021	E_11d 9h	209	7402	4168	19.9
022	E_11d 9h	167	16019	9021	54
030	J_d0 9hr	160	303	171	1.1
031	J_d0 9hr	150	125	70	0.5
032	J_d0 9hr	150	221	124	0.8
033	J_d1 9hr	150	58	33	0.2
034	J_d1 8hr	150	94	53	0.4
035	J_d1 8hr	150	51	29	0.2
036	J_d2 8hr	140	107	60	0.4
037	J_d2 8hr	131	104	59	0.5
038	J_d2 9hr	150	279	157	1

039	J_d3 9hr	150	46	26	0.2
040	J_d3 9hr	150	88	50	0.3
041	J_d3 9hr	140	53	30	0.2
042	J_d4 9h	75	85	48	0.6
043	J_d4 9h	75	103	58	0.8
044	J_d4 9h	75	121	68	0.9
045	J_d5 8h	75	109	61	0.8
046	J_d5 8h	75	169	95	1.3
047	J_d5 8h	75	89	50	0.7
048	J_d6 9hr	75	396	223	3
049	J_d6 9hr	75	383	215	2.9
050	J_d6 8 hr	75	76	43	0.6
051	J_d7 9 hr	75	139	78	1
052	J_d7 9hr	66	108	61	0.9
053	J_d7 9hr	66	73	41	0.6
054	J_d8 9hr	75	134	76	1
055	J_d8 9hr	75	156	88	1.2
056	J_d8 9hr	75	n.d.	0	0
057	J_d9 - J4	45	n.d.	0	0
058	J_d9 - J4	45	43	24	0.5
059	J_d9 - J4	40	n.d.	0	0

Figure 2 supporting data 2. Age of samples extracted for ecdysteroid measurements (given as 20 hydroxyecdysone equivalents). Age of samples from midpoint of 12 hr egg collections. Hatching occurred at 11.5 days after egg laying (AEL)

age (days AEL)	Sample 1 pg/individual	Sample 2 pg/individual	Sample 3 pg/individual	Sample 4 pg/individual	Sample 5 pg/individual	Average pg/individual
1	4.2	7.1				5.7
1.5	6.8	7.7				7.2
2	8	7.1				7.5
2.5	23	8.8	11.9			14.6
3	11	11.7	14.8			12.5
3.5	9.5	13.4	19.2			14.1
4	10	11.5	17.1			12.8
4.5	5.9	8.2	9.6			7.9
5	8.5	6.8	10.6			8.6
5.5	7.4	12.2	14			11.2
6	15.8	9.6	18.9			14.7
6.5	39.5	74.7	128.1			80.7
7	82.6	233				157.8
7.5	34.3	35	20.8			30.1
8	14.84	23				18.9
8.5	13.2	11	12.4	19.8	29	17
9	12.2	20	11			14.4
9.5	12.2	20	14.2	12.6	41.8	20.2
10	12.9	14.8	14.3			14
10.5	14.3	17.4	17.1	25	16.2	18
11	138.7	198.6	237.7			191.7
11.5	66.3	42.7	82.7	72.4		66.1
12.5	32.1	29				30.6
13.5	44	51.9				48
14.5	67.7	91.3	27.6			62.2
15.5	18.5	34.8	16.8			23.4
16.5	25	19.8				22.4
17.5	21.3	27				29

Figure 3 Source data 3. Primers used for real-time PCR.

gene	sequence accession number (NCBI)	forward primer (5'-3')	reverse primer (5'-3')
Met	JN416986.1	TACTCCATCCACACAGTCAAGG	TTCCGTGATTCGACGATCTCTC
Kr-h1	JN416989.1	ACTCCGTCGAATGGTACTAGTG	GTTCTTGCATGGGAGGAAACTG
myo	GASN02042720.1	TTCAACAAGCAAGCCCACAAG	ACACCGATCCACTACCATTCC
rp49	AB689035.1	CTAAAGAGGAACTGGCGCAAAC	GTTTAGTCTTCTTGGCGCTTCC

Figure 4 Source Data 1. The progression of embryonic development of embryos treated with solvent or 7-ethoxyprecocene (7EP) at 3.5 days of development. Developmental rescue was attempted by subsequent treatment with a juvenile hormone mimic (pyriproxyfen) at the indicated developmental time thereafter. air: air appears between embryo and eggshell because of resorption of extraembryonic fluid; eye: appearance of eye pigment. Percent values are based on surviving embryos. *: these embryos blocked before dorsal closure because of the early timing of treatment with pyriproxyfen.

treatment	#	d 5.5	d 6.5	d 7.5	d 8.5	d 9.5	d 10.5	d 11.5	d 12.5	d 13.5
none	30	eye: 0	eye: 23 [77%]	eye: 29 [97%]	air: 0 [0%]; dead: 1	air: 8 [28%]	air: 27 [93%]	air: 29 [100%]	hatch: 21 [72%]	
cyclohexane (d3.5)	30	eye: 0	eye: 26 [87%]	eye: 30 [100%]	air: 0 [0%]	air: 23 [77%]; dead: 2	air: 28 [100%]	air: 28 [100%]; hatch: 4 [14%]	hatch: 28 [100%]	
1 ug 7EP (d3.5)	30	eye: 0	eye: 30 [100%]	eye: 30 [100%]	air: 0 [0%]; dead: 1	air: 2 [7%]	air: 3 [10%]; dead: 1	air: 4 [14%]; hatch: 1 [3%]	air: 4 [14%]; hatch: 3 [11%]	
1 ug 7EP [d3.5]; 1ng Pyri [d6.5]	15	eye: 0	eye: 13 [87%]	eye: 30 [100%]	air: 0 [0%]*	air: 0 [0%]*	air: 0 [0%]*	air: 0 [0%]*	air: 0 [0%]*	
1 ug 7EP [d3.5]; 1ng Pyri [d7.5]	30	eye: 0	eye: 27 [90%]	eye: 29 [97%]	air: 1 [3%]; dead: 1	air: 11 [38%]	air: 17 [57%]	air: 17 [57%]; hatch: 10 [34%]	air: 17 [57%]; hatch 12 [41%]	
1 ug 7EP [d3.5]; 1ng Pyri [d8.5]	30	eye: 0	eye: 22 [73%]; dead: 1	eye: 27 [93%]	air: 0 [0%]	air: 16 [55%]	air: 29 [100%]	air: 29 [100%]; hatch: 1 [3%]	air: 29 [100%]; hatch: 27 [93%]	
1 ug 7EP [d3.5]; 1ng Pyri [d9.5]	30	eye: 0	eye: 27 [90%]	eye: 27 [90%]; dead: 1	air: 0 [0%]	air: 0 [0%]	air: 14 [50%]	air: 26 [93%]; hatch: 0 [0%]	air: 26 [93%]; hatch: 5 [18%]	hatch: 26 [93%]

Figure 6 Source data 1. The relationship of the time of treatment with a JH mimic (1 ng pyriproxyfen) to when embryonic development subsequently stalled. EEF: extraembryonic fluid; pre-dorsal closure was evident by dorsal closure to the neck region, but the posterior head capsule had not fully formed.

stage attained age at treatment with JHm	N	Germ band	extended limb buds	post katatrepsis	eye pigment	pre-dorsal closure	dorsal closure	resorb EEF	hatch
0.5d	16	12 [75%]	9 [56%]						
1.5d	18	18 [100%]	18 [100%]						
2.5d	20	20 [100%]	20 [100%]						
3.5d	21	21 [100%]	21 [100%]	21 [100%]	11 [52%]				
4.5d	21	21 [100%]	21 [100%]	21 [100%]	21 [100%]	21 [100%]	0 [0%]		
5.5d	15	15 [100%]	15 [100%]	15 [100%]	15 [100%]	14 [94%]	1 [6%]		
6.5d	19	19 [100%]	19 [100%]	19 [100%]	19 [100%]	19 [100%]	19 [100%]	15 [79%]	13 [68%]
7.5d	15	15 [100%]	15 [100%]	15 [100%]	15 [100%]	15 [100%]	15 [100%]	15 [100%]	15 [100%]

Figure 7 Source data 1. The effects of early treatment with a JH mimic (1 ng pyriproxyfen) on the subsequent proliferative activity in the embryonic limb buds indicated by the number of limb cells expressing phosphor histone H3 (pPH3). N is the number of embryos scored for each treatment.

Treatment	score embryos	N	Average number of pHH3 positive cells/limb	average
Controls: treat at 1.5 d AEL				
cyclohexane 1.5 d	2.5 d AEL	3	11.3, 12.7, 9	11
cyclohexane 1.5 d	3.5 d AEL	13	12.8, 17.6, 13.5, 17.7, 16. 10, 15, 18, 12.5, 22, 12, 16, 16.5.	15.3
cyclohexane 1.5 d	4.5 d AEL	11	21.3, 29.2, 22.5, 24, 25, 29.3, 23, 24.3, 23, 26, 33.5	25.6
cyclohexane 1.5 d	5.5 d AEL	10	20, 22.3, 21, 20.3, 22.7, 27.3, 25.7, 31, 29, 19.5	23.9
cyclohexane 1.5 d	6.5 d AEL	6	11.3, 11, 14, 10.6, 15.3, 14.3	12.8
cyclohexane 1.5 d	7.5 d AEL	4	7.3, 8, 7.3, 7, 3	7.5
JHm: treat at 1.5 d AEL				
JHm 1.5 d	2.5 d AEL	3	14, 13, 10.3	12.4
JHm 1.5 d	3.5 d AEL	11	17, 15.5, 16.4, 14.7, 16.7, 15.5, 4.8, 13.3, 14, 11, 5.8	13.2
JHm 1.5 d	4.5 d AEL	11	2.7, 3.7, 3.2, 1., 0., 1.7, 0.3, 0, 1.5, 1.7, 0.7	1.5
JHm 1.5 d	5.5 d AEL	13	7, 9, 4.5, 6.3, 2, 5.3, 2, 0.3, 0, 0.3, 0.2, 3.3, 0	3.1
JHm 1.5 d	6.5 d AEL	14	5.3, 0, 4.3, 0.6, 1.5, 0.6, 1.5, 0, 0, 0, 0.3, 0, 4, 1.6, 0	1.4
JHm 1.5 d	7.5 d AEL	8	0,0.7, 0, 0.7, 0, 0.3, 0, 0,	0.2

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Reviewer #1 (Public Review):

Summary:
This paper provides strong evidence for the roles of JH in an ametabolous insect species. In particular, it demonstrates that:
• JH shifts embryogenesis from a growth mode to a differentiation mode and is responsible for terminal differentiation during embryogenesis. This, and other JH roles, are first suggested as correlations, based on the timing of JH peaks, but then experimentally demonstrated using JH antagonists and rescue thereof with JH mimic. This is a robust approach and the experimental results are very convincing.
• JH redirects ecdysone-induced molting to direct formation of a more mature cuticle
• Kr-h1 is downstream of JH in Thermobia, as it is in other insects, and is a likely mediator of many JH effects
• The results support the proposed model that an ancestral role of JH in promoting and maintaining differentiation was coopted during insect radiations to drive the evolution of metamorphosis. However, alternate evolutionary scenarios should also be considered.

Strengths:

Overall, this is a beautiful, in-depth student. The paper is well-written and clear. The background places the work in a broad context and shows its importance in understanding fundamental questions about insect biology. The researchers are leaders in the field, and a strength of this manuscript is their use of a variety of different approaches (enzymatic assays, gene expression, agonists & antagonists, analysis of morphology using different types of microscopy and detection, and more) to attack their research questions. The experimental data is clearly presented and carefully executed with appropriate controls and attention to detail. The 'multi-pronged' approach provides support for the conclusions from different angles, strengthening conclusions. In sum, the data presented are convincing and the conclusions about experimental outcomes are well-justified based on the results obtained.

Weaknesses:

This paper provides more detail than is likely needed for readers outside the field but also provides sufficient depth for those in the field. This is both a strength and a weakness. I would suggest the authors shorten some aspects of their text to make it more accessible to a broader audience. In particular, the discussion is very long and accompanied by two model figures. The discussion could be tightened up and much of the text used for a separate review

article (perhaps along with Figure 11) that would bring more attention to the proposed evolution of JH roles.

https://doi.org/10.7554/eLife.92643.2.sa2

Reviewer #2 (Public Review):

The authors have studied in detail the embryogenesis of the ametabolan insect Thermobia domestica. They have also measured the levels of the two most important hormones in insect development: juvenile hormone (JH) and ecdysteroids. The work then focuses on JH, whose occurrence concentrates in the final part (between 70 and 100%) of embryo development. Then, the authors used a precocene compound (7-ethoxyprecocene, or 7EP) to destroy the JH producing tissues in the embryo of the firebrat T. domestica, which allowed to unveil that this hormone is critically involved in the last steps of embryogenesis. The 7EP-treated embryos failed to resorb the extraembryonic fluid and did not hatch. More detailed observations showed that processes like the maturational growth of the eye, the lengthening of the foregut and posterior displacement of the midgut, and the detachment of the E2 cuticle, were impaired after the 7EP treatment. Importantly, a treatment with a JH mimic subsequent to the 7EP treatment restored the correct maturation of both the eye and the gut. It is worth noting that the timing of JH mimic application was essential for correcting the defects triggered by the treatment with 7EP.

This is a relevant result in itself since the role of JH in insect embryogenesis is a controversial topic. It seems to have an important role in hemimetabolan embryogenesis, but not so much in holometabolans. Intriguingly, it appears important for hatching, an observation made in hemimetabolan and in holometabolan embryos. Knowing that this role was already present in ametabolans is relevant from an evolutionary point of view, and knowing exactly why embryos do not hatch in the absence of JH, is relevant from the point of view of developmental biology.

Then, the authors describe a series of experiments applying the JH mimic in early embryogenesis, before the natural peak of JH occurs, and its effects on embryo development. Observations were made under different doses of JHm, and under different temporal windows of treatment. Higher doses triggered more severe effects, as expected, and different windows of application produced different effects. The most used combination was 1 ng JHm applied 1.5 days AEL, checking the effects 3 days later. Of note, 1.5 days AEL is about 15% embryonic development, whereas the natural peak of JH occurs around 85% embryonic development. In general, the ectopic application of JHm triggered a diversity of effects, generally leading to an arrest of development. Intriguingly, however, a number of embryos treated with 1 ng of JHm at 1.5 days AEL showed a precocious formation of myofibrils in the longitudinal muscles. Also, a number of embryos treated in the same way showed enhanced chitin deposition in the E1 procuticle and showed an advancement of at least a day in the deposition of the E2 cuticle.

While the experiments and observations are done with great care and are very exhaustive, I am not sure that the results reveal genuine JH functions. The effects triggered by a significant pulse of ectopic JHm when the embryo is 15% of the development will depend on the context: the transcriptome existing at that time, especially the cocktail of transcription factors. This explains why different application times produce different effects. This also explains why the timing of JHm application was essential for correcting the effects of 7EP treatment. In this reasoning, we must consider that the context at 85% development, when the JH peaks in natural conditions and plays its genuine functions, must be very different from the context at 15% development, when the JHm was applied in most of the experiments. In summary, I believe that the observations after the application of JHm reveal effects of the ectopic JHm, but not necessarily functions of the JH. If so, then the subsequent inferences made from the

premise that these ectopic treatments with JHm revealed JH functions are uncertain and should be interpreted with caution.

Those inferences affect not only the "JH and the progressive nature of embryonic molts" section, but also, the "Modifications in JH function during the evolution of hemimetabolous and holometabolous life histories" section, and the entire "Discussion". In addition to inferences built on uncertain functions, the sections mentioned, especially the Discussion, I think suffer from too many poorly justified speculations. I love speculation in science, it is necessary and fruitful. But it must be practiced within limits of reasonableness, especially when expressed in a formal journal.

Finally, In the section "Modifications in JH function during the evolution of hemimetabolous and holometabolous life", it is not clear the bridge that connects the observations on the embryo of Thermobia and the evolution of modified life cycles, hemimetabolan and holometabolan.

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Reviewer #3 (Public Review):

Summary:

In this manuscript, the authors use inhibitors and mimetics of juvenile hormone (JH) to demonstrate that JH has a key role in late embryonic development in Thermobia, specifically in gut and eye development but also resorption of the extraembryonic fluid and hatching. They then exogenously apply JH early in development (when it is not normally present) to examine the biological effects of JH at these stages. This causes a plethora of defects including developmental arrest, deposition of chitin, limb development, and enhanced muscle differentiation. The authors interpret these early effects on development as JH being important for the shift from morphogenetic growth to differentiation - a role that they speculate may have facilitated the evolution of metamorphosis (hemi- and holo-metaboly). This paper will be of interest to insect evo-devo researchers, particularly those with interests in the evolution of metamorphosis.

Strengths:

The experiments are generally conducted very well with appropriate controls and the authors have included a very detailed analysis of the phenotypes.
The manuscript significantly advances our understanding of Thermobia development and the role of JH in Thermobia development.
The authors interpret this data to present some hypotheses regarding the role of JH in the evolution of metamorphosis, some aspects of which can be addressed by future studies.

Weaknesses:

The results are based on using inhibitors and mimetics of JH and there was no attempt to discern immediate effects of JH from downstream effects. The authors show, for instance, that the transcription of myoglianin is responsive to JH levels, it would have been interesting to see if any of the phenotypic effects are due to myoglianin upregulation/suppression (using RNAi for example). These kinds of experiments will be necessary to fully work out if and how the JH regulatory network has been co-opted into metamorphosis.

The results generally support the authors' conclusions. However, the discussion contains a lot of speculation and some far-reaching conclusions are made about the role of JH and how it became co-opted into controlling metamorphosis. There are some interesting hypotheses presented and the author's speculations are consistent with the data presented. However, it is

difficult to make evolutionary inferences from a single data point as although Thermobia is a basally branching insect, the lineage giving rise to Thermobia diverged from the lineages giving rise to the holo- and hemimetabolous insects approx.. 400 mya and it is possible that the effects of JH seen in Thermobia reflect lineage-specific effects rather than the 'ancestral state'. The authors ignore the possibility that there has been substantial rewiring of the networks that are JH responsive across these 400 my. I would encourage the authors to temper some of the discussion of these hypotheses and include some of the limitations of their inferences regarding the role of JH in the evolution of metamorphosis in their discussion.

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Author Response

The following is the authors' response to the original reviews.

We appreciate the care and the detail shown by the Reviewers. Their comments have made our article more focused and more accessible to a general audience.

We would like to begin with a comment about the last sentence of the "eLife assessment". The evolution of metamorphosis in insects was a major triumph in animal evolution that subsequently impacted almost every aspect of plant and animal evolution in the terrestrial and freshwater aquatic biospheres. Unlike the metamorphoses of most other groups, whose evolutions are lost in time, insect evolution arose relatively recently (~400 mya) and insect orders have branched off at various points in this evolution and have persisted to modern times. Although these "relic" groups also have undergone millions of years of evolution and specialization, they still provide us with windows into how this progression may have come about. The study of these groups provides a unique opportunity to explore the mechanisms that underlie major life history shifts and should be of interest to anyone interested in evolution – not just entomologists.

> ***Reviewer #1 (Public Review):***
>
> *Summary:*
>
> *This paper provides strong evidence for the roles of JH in an ametabolous insect species. In particular, it demonstrates that:*
>
> *• JH shifts embryogenesis from a growth mode to a differentiation mode and is responsible for terminal differentiation during embryogenesis. This, and other JH roles, are first suggested as correlations, based on the timing of JH peaks, but then experimentally demonstrated using JH antagonists and rescue thereof with JH mimic. This is a robust approach and the experimental results are very convincing.*
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> *• JH redirects ecdysone-induced molting to direct formation of a more mature cuticle*
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>
> *• The results support the proposed model that an ancestral role of JH in promoting and maintaining differentiation was coopted during insect radiations to drive the evolution of metamorphosis. However, alternate evolutionary scenarios should also be considered.*
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> *Strengths:*
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> *Overall, this is a beautiful, in-depth student. The paper is well-written and clear. The background places the work in a broad context and shows its importance in*

> *understanding fundamental questions about insect biology. The researchers are leaders in the field, and a strength of this manuscript is their use of a variety of different approaches (enzymatic assays, gene expression, agonists & antagonists, analysis of morphology using different types of microscopy and detection, and more) to attack their research questions. The experimental data is clearly presented and carefully executed with appropriate controls and attention to detail. The 'multi-pronged' approach provides support for the conclusions from different angles, strengthening conclusions. In sum, the data presented are convincing and the conclusions about experimental outcomes are well-justified based on the results obtained.*
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> *This paper provides more detail than is likely needed for readers outside the field but also provides sufficient depth for those in the field. This is both a strength and a weakness. I would suggest the authors shorten some aspects of their text to make it more accessible to a broader audience. In particular, the discussion is very long and accompanied by two model figures. The discussion could be tightened up and much of the text used for a separate review article (perhaps along with Figure 11) that would bring more attention to the proposed evolution of JH roles.*

We appreciate the comments about the strengths and weaknesses of the paper. To deal with the weaknesses, we have condensed some of the Results to make them less cumbersome and the Discussion has been completely revised, keeping a sharp focus on the actions of JH in Thermobia embryos and how these actions relate to the status quo functions of JH in insects with metamorphosis. As part of the revision of the Discussion, we have replaced Figures 10 and 11.

> ***Reviewer #1 (Recommendations For The Authors):***
>
> *In keeping with my public review, this paper is very strong and I have very few suggestions for improvement. They are:*
>
> *(1) Thermobia are extant insects and are not ancestral insects. It is likely that they retain features found in an insect ancestor. However, these insects have been evolving for a very long time, and for any one feature, many changes may have occurred, both gain and loss of gene function and morphology. Further, even for morphological features present in an extant species that are the same as an ancestor, genetic pathways regulating this feature may have changed over time (see for examples papers from the Haag and Pick labs). Although I realize this is a small, possibly almost semantic point, I feel it is important to be precise here. For example, in the title, "before" is speculative as there could have been a different role in the ancestor with the role in embryogenesis arising in lineages leading to Thermobia; similarly in the abstract, "this ancestral role of JH' is an overstatement since we cannot actually measure the ancestral role.*

Since the title has already been cited in a Perspectives review, we decided to keep the title as is.

> *(2) I don't understand the results in Met and myo in Fig. 3B. Perhaps include them in the explanation of Fig.3 and not after the description of Fig. 4 and explain them in more detail (or perhaps not include them at all?). I don't really understand the statistical analysis of these panels either.*

We have revised the figure legends to explain the statistics.

> *(3) Another point regarding language - talking about the embryo being "able" to go through a developmental stage implies decision-making. I would suggest dropping that wording (e.g, in the description of Fig. 5C). Similarly, in explaining Fig. 6B, it would be more correct to say "JH treatment no longer inhibited" than as written "could no longer inhibit" (implying 'no matter how hard it tried, it still couldn't do it')*

We have removed the “can’t” wording. Figure 6 has been revised

> ***Reviewer #2 (Public Review):***
>
> *The authors have studied in detail the embryogenesis of the ametabolan insect Thermobia domestica. They have also measured the levels of the two most important hormones in insect development: juvenile hormone (JH) and ecdysteroids. The work then focuses on JH, whose occurrence concentrates in the final part (between 70 and 100%) of embryo development. Then, the authors used a precocene compound (7-ethoxyprecocene, or 7EP) to destroy the JH producing tissues in the embryo of the firebrat T. domestica, which allowed to unveil that this hormone is critically involved in the last steps of embryogenesis. The 7EP-treated embryos failed to resorb the extraembryonic fluid and did not hatch. More detailed observations showed that processes like the maturational growth of the eye, the lengthening of the foregut and posterior displacement of the midgut, and the detachment of the E2 cuticle, were impaired after the 7EP treatment. Importantly, a treatment with a JH mimic subsequent to the 7EP treatment restored the correct maturation of both the eye and the gut. It is worth noting that the timing of JH mimic application was essential for correcting the defects triggered by the treatment with 7EP.*
>
> *This is a relevant result in itself since the role of JH in insect embryogenesis is a controversial topic. It seems to have an important role in hemimetabolan embryogenesis, but not so much in holometabolans. Intriguingly, it appears important for hatching, an observation made in hemimetabolan and in holometabolan embryos. Knowing that this role was already present in ametabolans is relevant from an evolutionary point of view, and knowing exactly why embryos do not hatch in the absence of JH, is relevant from the point of view of developmental biology.*

The unique and intriguing aspect of juvenile hormone is its status quo action in the control of metamorphosis. Our reason for dealing with an insect group that branched off from the line of insects that eventually evolved metamorphosis, was to gain insight into the ancestral functions of this hormone. Our data from Thermobia as well as that from grasshoppers and crickets indicate that the developmental actions of JH were originally confined to embryogenesis where it promoted the terminal differentiation of the embryo. Its actions in promoting differentiation also included suppressing morphogenesis. This latter function was not pronounced during embryogenesis because JH only appeared after morphogenesis was essentially completed. However, it was a preadaptation that proved useful in more derived insects that delayed aspects of morphogenesis into the postembryonic realm. JH was then used postembryonically to inhibit morphogenesis until late in juvenile growth when JH disappears, and this inhibition is released.

> *Then, the authors describe a series of experiments applying the JH mimic in early embryogenesis, before the natural peak of JH occurs, and its effects on embryo development. Observations were made under different doses of JHm, and under different temporal windows of treatment. Higher doses triggered more severe effects, as expected, and different windows of application produced different effects. The most used combination was 1 ng JHm applied 1.5 days AEL, checking the effects 3 days later. Of note, 1.5 days AEL is about 15% embryonic development, whereas the natural peak of JH*

> *occurs around 85% embryonic development. In general, the ectopic application of JHm triggered a diversity of effects, generally leading to an arrest of development. Intriguingly, however, a number of embryos treated with 1 ng of JHm at 1.5 days AEL showed a precocious formation of myofibrils in the longitudinal muscles. Also, a number of embryos treated in the same way showed enhanced chitin deposition in the E1 procuticle and showed an advancement of at least a day in the deposition of the E2 cuticle.*
>
> *While the experiments and observations are done with great care and are very exhaustive, I am not sure that the results reveal genuine JH functions. The effects triggered by a significant pulse of ectopic JHm when the embryo is 15% of the development will depend on the context: the transcriptome existing at that time, especially the cocktail of transcription factors. This explains why different application times produce different effects. This also explains why the timing of JHm application was essential for correcting the effects of 7EP treatment. In this reasoning, we must consider that the context at 85% development, when the JH peaks in natural conditions and plays its genuine functions, must be very different from the context at 15% development, when the JHm was applied in most of the experiments. In summary, I believe that the observations after the application of JHm reveal effects of the ectopic JHm, but not necessarily functions of the JH. If so, then the subsequent inferences made from the premise that these ectopic treatments with JHm revealed JH functions are uncertain and should be interpreted with caution.*

We disagree with the reviewer. An analogous situation would be in exploring gene function in which both gain-of-function and loss-of-function experiments often provide complementary insights into how a gene functions. We see JH effects only when its receptor, Met, is present and JH can induce its main effector protein, Kr-h1. The latter gives us confidence that we are looking at bona fide JH effects. We have also kept in mind, though, that the nature of the responding tissues is changing through time. Nevertheless, we see a consistent pattern of responses in the embryo and these can be related to its postembryonic effects in metamorphic insects.

> *Those inferences affect not only the "JH and the progressive nature of embryonic molts" section, but also, the "Modifications in JH function during the evolution of hemimetabolous and holometabolous life histories" section, and the entire "Discussion". In addition to inferences built on uncertain functions, the sections mentioned, especially the Discussion, I think suffer from too many poorly justified speculations. I love speculation in science, it is necessary and fruitful. But it must be practiced within limits of reasonableness, especially when expressed in a formal journal.*

We have tried to dial back the speculation.

> *Finally, In the section "Modifications in JH function during the evolution of hemimetabolous and holometabolous life", it is not clear the bridge that connects the observations on the embryo of Thermobia and the evolution of modified life cycles, hemimetabolan and holometabolan.*

Our Figure 12 should put this into perspective.

> ***Reviewer #2 (Recommendations For The Authors):***
>
> *Main points*
>
> *(1) Please, reduce the level of overinterpretation of ectopic treatment experiments with JHm, since the resulting observations represent effects, but not necessarily functions of*

> *JH.*

We have revised this section to indicate that the “effects” of ectopic treatments provide insights into the function of JH. Using a genetic analogy, both “loss-of-function” and “gain-of-function” experiments provide insights into a given gene. (see response to Public Comments)

> *(2) Especially in the sections "JH and the progressive nature of embryonic molts" and "Modifications in JH function during the evolution of hemimetabolous and holometabolous life histories", and the entire "Discussion", please keep the level of speculation within reasonable limits, avoiding especially the inference of conclusions on the basis of speculation, itself based on previous speculation.*

We have toned down some of the speculation and provided reasons why it is worth suggesting.

> *(3) Please revisit the argued roles of myoglianin in the story, in light of its effects as an inhibitor of JH production, repressing the expression of JHAMT, as has been reliably demonstrated in hemimetabolan species (DOI: 10.1073/pnas.1600612113 and DOI: 10.1096/ fj.201801511R).*

Our appreciation to the reviewer. We are more explicit about the relationship between JH and myo.

> *Minor points*
>
> *(4) Please keep the consistency of the scientific binomial nomenclature for the species mentioned. For example, read "Manduca sexta" (in italics) at the first mention, and then "M. sexta" (in italics) in successive mentions (instead of reading "Manduca" on page 17, and then "Manduca sexta" on page 18, for example). The same for "Drosophila" ("Drosophila melanogaster" first, and then "D. melanogaster"), "Thermobia" ("Thermobia domestica" first, and then "T. domestica"), etc. In the figure legends, I recommend using the complete name: Thermobia domestica, in the main heading.*

Where there is no possibility of confusion, we intend to use Thermobia, rather than T. domestica, etc. We think that it is easier for a non-specialist to read and it is commonly done in endocrine papers.

> *(5) There is no purpose in evolution and biological processes. Thus, I suggest avoiding expressions that have a teleological aftertaste. For example (capitals are mine), on p. 3 "appears to have been extended into postembryonic life where it acts TO antagonize morphogenic and allow the maintenance of a juvenile state".*

We have tried to avoid teleological wording.

> *(6) The title "The embryonic role of juvenile hormone in the firebrat, Thermobia domestica, reveals its function before its involvement in metamorphosis" contains a redundancy ("role" and "function"), and an apparent obviousness ("before its involvement in metamorphosis"). I suggest a more straightforward title. Something like "Juvenile hormone plays developmental functions in the embryo of the firebrat Thermobia domestica, which predate its status quo action in metamorphosis".*

As noted above, we are retaining the title since it has already been cited.

> *(7) Page 2. "The transition from larva to adult then occurred through a transitional stage, the pupa, thereby providing the three-part life history diagnostic of the "complete metamorphosis" exhibited by holometabolous insects (reviews: Jindra, 2019; Truman & Riddiford, 2002, 2019)". I suggest adding the reference ISBN: 9780128130209 9 7 8 - 0 - 1 2 - 8 1 3 0 2 0 - 9, as the most comprehensive and recent review on complete metamorphosis.*

Done

> *(8) Page 3. "These severe developmental effects suggest that the developmental role of JH in insects was initially CONFINED to the embryonic domain" (capitals are mine). This appears contradictory with the observations of Watson, 1967, on the relationships between the apparition of scales and JH, mentioned shortly before by the authors.*

This is explained in the Discussion. Although JH can suppress scale appearance in the J4 stage, we have not been able to show that scales appearance is caused by changes in the juvenile JH titer.

> *(9) Page 4. "we measured JH III levels during Thermobia embryogenesis at daily intervals starting at 5 d AEL". Why not before, like in the case of ecdysteroids? The authors might perhaps argue that the levels of Kr-h1 expression are consistently low from the very beginning, according to Fernandez-Nicolas et al, 2022 (reference cited later in the manuscript).*
>
> *(10) Page 4. "Ecdysteroid titers through embryogenesis and the early juvenile instars were measured using the enzyme immunoassay method (Porcheron et al., 1989) that is optimized for detecting 20-hydroxyecdysone (20E)". The antibody generated by Porcheron (and now sold by Cayman) recognizes ecdysone and 20-hydroxyecdysone alike. But that's not relevant here. I would refer to "ecdysteroids" when mentioning measurements. Also in figure 2B (and "juvenile hormone III" without the formula, in Panel A, for harmonization). And I would not expand on specifications, like those at the beginning of page 5, or towards the end of page*

We thank the reviewer for this important correction.

> *(12) ("the fact that we detected only a slight rise in ecdysteroids at this time (Fig 2B) is likely due to the assay that we used being designed to detect 20E rather than ecdysone").*

Omitted.

> *(11) Page 5. "Low levels of Kr-h1 transcripts were present at 12 hr after egg deposition, but then were not detected until about 6 d AEL when JH-III first appeared". There is a very precise Kr-h1 pattern in Fernandez-Nicolas et al. 2023 (reference mentioned later in the manuscript).*
>
> *(12) Page 5. "notably myoglianin (myo), have become prominent as agents that promote the competence and execution of metamorphosis in holometabolous and hemimetabolous insects (He et al., 2020; Awasaki et al., 2011)". See my note 3 above.*

The myoglianin issue has been revised.

> *(13) Page 5. "a drug that suppresses JH production". Rather, "a drug that destroys the JH producing tissues". Why the way, do the authors know when the CA are formed in T. domestica embryo development?*

We prefer to keep our original wording. There have been some cases in which precocene has blocked JH production but did not kill the CA cells. We do not have observations that show that 7EP kills the CA cells in Thermobia embryos.

> *(14) Page 5. "subsequent treatment with a JHm". I would say here that the JHm is pyriproxyfen, not on page 6 or page 7. Thus, to be consistent, after the first mention of "pyriproxyfen (JHm)" on page 5, I'd consistently use the abbreviation "JHm".*
>
> *(15) Page 9. "Limb loss in such embryos was often STOCHASTIC, i.e., in a given embryo some limbs were completely lost while others were maintained in a reduced state" (capitals are mine). The meaning of "stochastic" is random, involving a random variable; it is a concept usually associated to probability theory and related fields. I suggest using the less specialized word "variable", since to ascertain that the values are really stochastic would require specific mathematical approaches.*

We are still using stochastic because the loss is random.

> *(16) Page 10. "9E). Indeed, the JH treatment redirects the molt to be more like that to the J2 stage, rather than to the E2 (= J1) stage". Probably too assertive given the evidence available (see my points 1 and 2 above).*

We do not see a problem with our conclusion. In response to the JHm treatment, the embryo produced a smooth, rather than a “pebbly” cuticle, failed to make the J1-specific egg tooth, and attempted to make cuticular lenses (a J2 feature). This ability of premature JH exposure to cause embryos to “skip” a stage is also seen in locusts (Truman & Riddiford, 1999) and crickets (Erezyilmaz et al., 2004). The JHm treatment resulted in the production of smooth cuticle, lack of a hatching tooth, and an attempt to make cuticular lenses.

> *(17) Page 11. "early JHM treatment", read "early JHm treatment".*

Corrected

> *(18) Page 11. "likely. A target of JH, and likely Kr-h1, in Thermobia is myoglianin...". Please see my notes 1, 2, and especially 3, above.*

This has been revised

> *(19) Page 13. "the locust, Locusta americana (Aboulafia-Baginshy et al.,1984)". Please read "the locust, Locusta migratoria (Aboulafia-Baginshy et al.,1984)".*

Corrected

> *(20) Page 13 "Acheta domesticus" three times. The correct name now is "Acheta domestica", after harmonizing the declension of the specific name with the generic one. See additionally my note 4 above.*

Acheta domesticus has been used in hundreds (thousands?) of papers since it was originally named by Linnaeus. We will continue to use it.

> *(21) Page 15, "(also called the vermiform larva (Bernays, 1971) redirects embryonic development to form an embryo with proportions, cuticular pigmentation, cuticular sculpturing and bristles characteristic of a nymph, while pronymph modifications, such as the cuticular surface sculpturing (Bernays, 1971)". The reference "Bernays, 1971" is indeed "Bergot et al., 1971".*

There was a mistake in the references. The Bernays reference was omitted from the revised Discussion

> *(22) Page 16. "Since JH also induces Kr-h1 in embryos of many insects, including Thermobia". I'm not sure that this has been studied in many insects. In any case, any reference would be useful.*
>
> *(23) Page 17. "Tribolium casteneum". Please read "Tribolium castaneum".*

Changed

> *(24) Page 17. "...results in a permanent larva that continues to molt well after it has surpassed its critical weight (He et al., 2019)". The paper of He et al., 2019 is preceded by two key papers that previously demonstrate (and in hemimetabolan insects) that myoglianin is a determining factor in the preparation for metamorphosis: DOI: 10.1073/pnas.1600612113 and DOI: 10.1096/ fj.201801511R). See my note 3 above.*

Corrected in revision

> *(25) Page 18. "These persisting embryonic primordia join the wing primordia in delaying their morphogenesis into postembryonic life". This reader does not understand this sentence.*

Made clearer in the revision.

> *(26) Page 18. "is first possible in the commercial silkworm (Daimon et al., 2015)". Please mention the scientific Latin name of the species, Bombyx mori.*
>
> *(27) Page 19. "The functioning of farnesol derivatives in growth versus differentiation control extends deep into the eukaryotes.../... this capacity was eventually exploited by the insects to provide the hormonal system that regulates their metamorphosis". This information appears quite out of place.*

We have retained this point.

> *(28) Page 21. Heading "Hormones". I suggest using the heading "Bioactive compounds", as neither pyriproxyfen nor 7-ethoxyprecocene are hormones.*

Done

> *(29) Page 29, legend of figure 1. "Photomicrographs" is somewhat redundant. The technical word is "micrographs". "Thermobia domestica" appears in the explanation of panel C, but this is not necessary, as the name appears in the main heading of the legend.*

Done

> *(30) Page 30, legend of figure 2. Panel B, see my comment 10 above. Why embryonic age is expressed in % embryo development in panel C (and in days in panels A and B)?*

All have been converted to days AEL

> *(31) Page 35, legend of figure 5. "Photomicrograph" see my note 28 above.*

Done

> *(32) Page 40, figure 10. In panel A, the indication of the properties of JH is misleading. The arrow going to promoting differentiation and maturation is OK, but the repression sign that indicates suppression of morphogenetic growth and cell determination seems to suggest that JH has retroactive effects. In panel B, I suggest to label "Flies" instead of "Higher Diptera", which is an old-fashioned term. In any case, see my general comments 1 and 2, above, about speculation.*

Figure has been completely revised

> *(33) Figure 11. See my general comments 1 and 2, above, about speculation.*

Figure has been revised

> ***Reviewer #3 (Public Review):***
>
> *Summary:*
>
> *In this manuscript, the authors use inhibitors and mimetics of juvenile hormone (JH) to demonstrate that JH has a key role in late embryonic development in Thermobia, specifically in gut and eye development but also resorption of the extraembryonic fluid and hatching. They then exogenously apply JH early in development (when it is not normally present) to examine the biological effects of JH at these stages. This causes a plethora of defects including developmental arrest, deposition of chitin, limb development, and enhanced muscle differentiation. The authors interpret these early effects on development as JH being important for the shift from morphogenetic growth to differentiation - a role that they speculate may have facilitated the evolution of metamorphosis (hemi- and holo-metaboly). This paper will be of interest to insect evo-devo researchers, particularly those with interests in the evolution of metamorphosis.*
>
> *Strengths:*
>
> *The experiments are generally conducted very well with appropriate controls and the authors have included a very detailed analysis of the phenotypes.*
>
> *The manuscript significantly advances our understanding of Thermobia development and the role of JH in Thermobia development.*
>
> *The authors interpret this data to present some hypotheses regarding the role of JH in the evolution of metamorphosis, some aspects of which can be addressed by future studies.*
>
> *Weaknesses:*
>
> *The results are based on using inhibitors and mimetics of JH and there was no attempt to discern immediate effects of JH from downstream effects. The authors show, for instance, that the transcription of myoglianin is responsive to JH levels, it would have been interesting to see if any of the phenotypic effects are due to myoglianin upregulation/suppression (using RNAi for example). These kinds of experiments will be necessary to fully work out if and how the JH regulatory network has been co-opted into metamorphosis.*

We agree completely and should be a feature of future work.

> *The results generally support the authors' conclusions. However, the discussion contains a lot of speculation and some far-reaching conclusions are made about the role of JH and how it became co-opted into controlling metamorphosis. There are some interesting hypotheses presented and the author's speculations are consistent with the data presented. However, it is difficult to make evolutionary inferences from a single data point as although Thermobia is a basally branching insect, the lineage giving rise to Thermobia diverged from the lineages giving rise to the holo- and hemimetabolous insects approx.. 400 mya and it is possible that the effects of JH seen in Thermobia reflect lineage-specific effects rather than the 'ancestral state'. The authors ignore the possibility that there has been substantial rewiring of the networks that are JH responsive across these 400 my. I would encourage the authors to temper some of the discussion of these hypotheses and include some of the limitations of their inferences regarding the role of JH in the evolution of metamorphosis in their discussion.*

We have tried to be less all-encompassing in the Discussion. The strongest comparisons can be made between ametabolous and hemimetabolous insects and we have focused most of the Discussion on the role of JH in that transition. We still include some discussion of holometabolous insects because the ancestral embryonic functions of JH may be somehow related to the unusual reappearance of JH in the prepupal period. We have reduced this discussion to only a few sentences.

> ***Reviewer #3 (Recommendations For The Authors):***
>
> *(1) The overall manuscript is very long (especially the discussion), and the main messages of the manuscript get lost in some of the details. I would suggest that the authors move some of the results to the supplementary material (e.g. it might be possible to put a lot of the detail of Thermobia embryogenesis into the supplementary text if the authors feel it is appropriate). The discussion contains a lot of speculation and I suggest the authors make this more concise. One example: At the moment there is a large section on the modification in JH function during the evolution of holo and hemi-metabolous life history strategies. There are some interesting ideas in this section and the authors do a good job of integrating their findings with the literature - but I would encourage the authors to limit the bulk of their discussion to the specific things that their results demonstrate. E.g. The first half of p17 contains too much detail, and the focus should be on the relationship with Thermobia (as at the bottom of p17).*

Section has been revised and is more focused

> *(2) I would also suggest a thorough proofread of the manuscript, I have highlighted some of the errors/points of confusion that I found in the list below - but this list is unlikely to be exhaustive . We appreciate catching the errors. Hopefully the final version is better proofed.*
>
> *(3) It might be me, but I found the wording in the second half of the abstract a bit confusing. Particularly the statement about the redeployment of morphogen systems - could this be stated more clearly?*

Abstract has been revised.

> *(4) Introduction*
>
> *a. "powered flight" rather than 'power flight'*

Done

> *b. 'brought about a hemimetabolous lifecycle' implies causality which hasn't been shown and directionality to evolution - suggest 'facilitated the evolution of a hemi...". Similar comment for 'subsequent step to complete metamorphosis'.*
>
> *c. Bottom of p2 - unclear whether you are referring to hemi- holo- or both*
>
> *d. Suggest removing sentence beginning "besides its effects..." as the relevance of the role of JH in caste isn't clear.*

Kept sentence but removed initial clause

> *e. State that Thermoia is a Zygentoma.*

Done

> *f. Throughout - full species names on first usage only, T. domestica on subsequent usages.*

We will continue to use genus names for the reason given above.

Gene names e.g. kr-h1 in italics.

> *g. 'antagonise morphogens"? rather than 'antagonise morphoentic'.*

Done

> *(5) Results*
>
> *a. Unclear why drawings are provided rather than embryonic images in Fig. 1A*

We think that the points can be made better with diagrams.

> *b. Top of p4, is 'slot' the correct word?*

Corrected

> *c. Unclear why the measurements of JHIII weren't measured before 5 days AEL, especially given that many of the manipulative experiments are at earlier time points than this. I appreciate that, based on kr-h1, levels that JHIII is also likely to be low.*
>
> *d. Reference for the late embryonic peak of 20E being responsible for the J2 cuticle?*

Clarified that this is an assumption

> *e. Clarify "some endocrine related transcripts" why were these ones in particular picked? Kr-h1 is a good transcriptional proxy for JH and Met is the JH-receptor, why myoglianin and not some of the other transcriptional proxies of neuroendocrine signalling?*

Hopefully, the choice is clearer.

> *f. Fig 2C rather than % embryo development for the gene expression data please represent this in days (to be consistent with your other figures).*

It is now consistent with other parts of figure.

> *g. In Fig. 3 the authors do t-tests, because there are three groups there needs to be some correction for multiple testing (e.g. Bonferroni) can the authors add this to the relevant methods section?*

We think that pair-wise comparisons are appropriate.

> *h. Fig. 3 legend: you note that you treat stage 2 juveniles with 7EP - I couldn't tell what AEL this corresponded to.*

This is after hatching so AEL does not apply.

> *i. Top of p7 'deformities' rather than 'derangements'?*

Done

> *j. Regarding the dosage effects of embryonic abnormalities - it would be good to include these in the supp material, as it convinces the reader that the effects you have seen aren't just due to toxicity.*

It is not clear what the objection is.

> *k. Bottom of p7 'problematic' not 'problematical'*

Done

> *l. P8 Why are the clusters of Its important? - provide a bit more interpretation for the reader here.*

This is clear in the revised version.

> *m. P9 Why is the modulation of transcription of kr-h1, met, and myo important in this context*

Explained

> *n. P9 'fig. 7F'? there is no Fig. 5F*

Thanks for catching the typo.

> *o. Fig. 7B add to the legend which treatment the dark and light points correspond to.*

We think it is obvious from the labeling on Fig 7B.

> *(6) Discussion:*
>
> *a. What do we know about how terminal differentiation is controlled in non-insect arthropods? Most of the discussion is focused on insects (which makes sense as JH is an insect-specific molecule), but if the authors are arguing the ancestral role of JH it would be useful to know how their findings relate to non-insect arthropods.*

We have not been able to find any information about systemic signals being involved in non-insect arthropods.

> *b. There is no Fig. 5E (are they referring to 7E?)*

Yes, it should have been Fig. 7E.

> *c. Is myoglianin a direct target of JH in other species?*

Other reports are in postembryonic stages and show that myoglianin suppresses JH production. Our paper is the first examination in embryos and we find that the opposite is true – i.e., that JH treatment suppresses myoglianin production. We suspect that these two signaling systems are mutually inhibitory. It would be interesting to see whether treatment of a post-critical weight larva with JH (which would induce a supernumerary larval molt) would also suppress myoglianin production (as we see in Thermobia embryos).

> *d. P12 What is the evidence that JH interacts with the first 20E peak to alter the embryonic cuticle?*

We are not sure what the issue is. The experimental fact is that treatment with JH before the E1 ecdysteroid peak causes the production of an altered E1 cuticle. We are faced with the question of why is this molt sensitive to JH when the latter will not appear until 3 or 4 days later? A possible answer is that the ecdysone response pathway has a component that has inherent JH sensitivity. The mosquito data suggest that Taiman provides another link between JH and ecdysone action

> *e. Top of p13 - this paragraph can be cut down substantially. Although this is evidence that JH can alter ecdysteriods - it is in a species that is 400 my derived from the target species. Is it likely to be the exact same mechanism? I would encourage the authors to distil and retain the most important points.*

This paragraph has been shortened and focused.

> *f. Bottom of p13 - what does this study add to this knowledge?*

The response of Thermobia embryos to JH treatment is qualitatively the same as seen in other short germband embryos. This similarity supports the assumption that the same responses would have been seen in their last common ancestor.

> *g. P19 the last paragraph in the conclusions is really peripherally relevant to the paper and is a bit of a stretch, I would encourage the authors to leave this section out.*

We agree that it is a stretch. JH and its precursor MF are the only sesquiterpene hormones. How did they come about to acquire this function? We think it is worth pointing out the farnesol metabolites have been associated with promoting differentiation in various eukaryotes. An ancient feature of these molecules in promoting (maintaining?) differentiation may have been exploited by the insects to develop a unique class of hormones. It is worth putting the idea out to be considered.

> *h. P19 "conclusions" rather than 'concluding speculations'.*

Changed as suggested.

> *Methods:*

> *It is standard practice to include at least two genes as reference genes for RT-qPCR analysis (https://doi.org/10.1186/gb-2002-3-7-research0034, https://doi.org/10.1373/clinchem.2008.112797) If there are large-scale differences in the tissues being compared (e.g. as there are here during development) then more than two reference genes may be required and a reference gene study (such as https://doi.org/10.3390%2Fgenes12010021) is appropriate. Have the authors confirmed that rp49 is stably expressed during the stages of Thermobia development that they assay here?*

We have explained our choice in the Methods.