© 2018. Published by The Company of Biologists Ltd | Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

RESEARCH ARTICLE

Effects of temperature on survival, moulting, and expression of neuropeptide and mTOR signalling genes in juvenile Dungeness crab (*Metacarcinus magister*)

Astrid C. Wittmann[1,*], Samiha A. M. Benrabaa[2], Diego Alejandro López-Cerón[2], Ernest S. Chang[3] and Donald L. Mykles[2]

ABSTRACT

Mechanistic target of rapamycin (mTOR) is a highly conserved protein kinase that controls cellular protein synthesis and energy homeostasis. We hypothesize that mTOR integrates intrinsic signals (moulting hormones) and extrinsic signals (thermal stress) to regulate moulting and growth in decapod crustaceans. The effects of temperature on survival, moulting and mRNA levels of mTOR signalling genes (*Mm-Rheb*, *Mm-mTOR*, *Mm-AMPKα*, *Mm-S6K* and *Mm-AKT*) and neuropeptides (*Mm-CHH* and *Mm-MIH*) were quantified in juvenile *Metacarcinus magister*. Crabs at different moult stages (12, 19 or 26 days postmoult) were transferred from ambient temperature (∼15°C) to temperatures between 5 and 30°C for up to 14 days. Survival was 97–100% from 5 to 20°C, but none survived at 25 or 30°C. Moult stage progression accelerated from 5 to 15°C, but did not accelerate further at 20°C. In eyestalk ganglia, *Mm-Rheb*, *Mm-AMPKα* and *Mm-AKT* mRNA levels decreased with increasing temperatures. *Mm-MIH* and *Mm-CHH* mRNA levels were lowest in the eyestalk ganglia of mid-premoult animals at 20°C. In the Y-organ, *Mm-Rheb* mRNA levels decreased with increasing temperature and increased during premoult, and were positively correlated with haemolymph ecdysteroid titre. In the heart, moult stage had no effect on mTOR signalling gene mRNA levels; only *Mm-Rheb*, *Mm-S6K* and *Mm-mTOR* mRNA levels were higher in intermoult animals at 10°C. These data suggest that temperature compensation of neuropeptide and mTOR signalling gene expression in the eyestalk ganglia and Y-organ contributes to regulate moulting in the 10 to 20°C range. The limited warm compensation in the heart may contribute to mortality at temperatures above 20°C.

KEY WORDS: Temperature acclimation, Moult cycle, Marine Crustacea, Gene expression, Ecdysteroid, mTOR

INTRODUCTION

Crustaceans, like other ecdysozoans, must shed their exoskeleton periodically to develop and grow (reviewed in Aiken and Waddy, 1992; Charmantier-Daures and Vernet, 2004; Skinner, 1985). Two endocrine glands regulate the moult cycle (reviewed in Chang and Mykles, 2011; Webster, 2015). The X-organ/sinus gland complex in the eyestalk ganglia secretes neuropeptides of the crustacean hyperglycaemic hormone (CHH) superfamily, including moult-inhibiting hormone (MIH) and CHH (reviewed in Webster, 2015; Webster et al., 2012). The neuropeptides act on the moulting gland (Y-organ), which synthesizes ecdysteroid moulting hormones. A drop in circulating MIH activates the Y-organ and the animal enters premoult (stages D_0 through D_4; Chang and Mykles, 2011; Skinner, 1985). Haemolymph ecdysteroid concentration increases approximately 100-fold from intermoult (C) to a peak in late premoult (D_2), then drops precipitously shortly before ecdysis and is lowest in postmoult (Thomton et al., 2006; reviewed in Mykles, 2011). In the target tissues, ecdysteroids are converted to their active forms and bind to nuclear receptors. This induces, for example, cuticle formation, partial resorption of the old exoskeleton, claw muscle atrophy and limb regenerate growth (Chang and Mykles, 2011; Mykles, 2011). Moulting is suspended or delayed by adverse environmental conditions, such as crowding or temperature stress, via direct or indirect inhibition of the Y-organ by neuropeptides (Aiken and Waddy, 1976; Anger and Spindler, 1987; Chung and Webster, 2005, Pitts et al., 2017; reviewed in Aiken and Waddy, 1992). Moult suspension occurs only in intermoult and early premoult animals. In mid and late premolt, the Y-organ becomes insensitive to neuropeptide control and the animal proceeds to ecdysis without delay (Anger, 1987; Chang and Mykles, 2011).

The highly conserved mTOR (mechanistic target of rapamycin) signalling pathway regulates cell growth and metabolism by integrating signals of energy, oxygen and nutrient supply, as well as of growth factors in organisms from yeast to mammals (reviewed in Reiling and Sabatini, 2006). It has been implicated in growth and moult regulation in insects (reviewed in Arquier et al., 2010; Nijhout et al., 2014) and crustaceans (Chang and Mykles, 2011; Das et al., 2016). mTOR activity is required for Y-organ activation, as rapamycin inhibits Y-organ ecdysteroid synthesis *in vitro* and lowers haemolymph ecdysteroid titre in *Gecarcinus lateralis* induced to moult by eyestalk ablation (Abuhagr et al., 2014b, 2016). Moreover, mTOR signalling genes, such as *Gl-mTOR*, *Gl-Rheb*, *Gl-AKT* and *Gl-S6K*, are upregulated in the Y-organ of *G. lateralis* induced to moult by multiple leg autotomy or eyestalk ablation (Abuhagr et al., 2014b, 2016; Das et al., 2018; Shyamal et al., 2018). Rheb (Ras homolog enriched in brain) is a GTP-binding protein that binds to mTOR and other proteins to form the active mTOR Complex 1 (mTORC1; reviewed in Saxton and Sabatini, 2017). Rheb activity is regulated upstream by protein kinase B (PKB, also known as AKT), which prevents inactivation of Rheb by the tuberous sclerosis complex (TSC1/2). A downstream target of mTORC1 is ribosomal protein S6 kinase (S6K), which is

[1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, 27570 Bremerhaven, Germany. [2]Colorado State University, Fort Collins, CO 80523, USA. [3]Bodega Marine Laboratory, University of California, Davis, Bodega Bay, CA 94923, USA.

*Author for correspondence (Astrid.Wittmann@awi.de)

A.C.W., 0000-0002-4839-5633

Received 25 June 2018; Accepted 27 August 2018

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

List of abbreviations

AKT	protein kinase B
AMPKα	AMP-dependent protein kinase α-subunit
C	intermoult
CHH	crustacean hyperglycaemic hormone
CW	carapace width
D_0	early premoult
D_1	mid premoult
$D_{2–3}$	late premoult
IGF	insulin/insulin-like growth factor
MIH	moult-inhibiting hormone
mTOR	mechanistic target of rapamycin
qPCR	quantitative polymerase chain reaction
RbS3	ribosomal protein S3
Rheb	ras homolog enriched in brain
S6K	ribosomal protein S6 kinase
t_0	before temperature incubation
t_{14}	after 14 days of temperature exposure

an important activator of protein synthesis and growth. mTORC1 can interact with transcription factors and coactivators involved in mitochondrial biogenesis and lipid metabolism and synthesis (e.g. peroxisome proliferator-activated receptors, PPARs; Sengupta et al., 2010). Transcriptomic analysis shows that mTOR activity, either directly or indirectly, affects the mRNA levels of thousands of contigs in the *G. lateralis* Y-organ (Shyamal et al., 2018). A negative regulator of mTORC1 is the cellular energy sensor AMP-dependent protein kinase (AMPK), which is activated at a low ATP/ADP ratio resulting from excessive exercise, hypoxia or acute thermal stress (Hardie et al., 2006; Reiling and Sabatini, 2006). During acute heat stress, reducing cellular energy consumption and growth by inactivation of mTOR may assure survival (Aramburu et al., 2014; Bandhakavi et al., 2008; Chou et al., 2012; Gibney et al., 2013; Hansen et al., 2007; Jarolim et al., 2013). In agreement with this, AMPK activation has been observed during acute temperature stress in marine ectotherms (Anttila et al., 2013; Frederich et al., 2009; Han et al., 2013). However, there is a paucity of studies addressing chronic, sublethal effects of temperature on mTOR activity. Transcriptional changes of raptor, an adaptor protein in mTORC1 (Clark et al., 2013), PPARs (Windisch et al., 2011) and regulators of the phosphatidylinositol 3-kinase (PI3*K*)-AKT signalling pathway upstream of mTOR (Windisch et al., 2014) indicate the importance of mTOR signalling for the reorganisation of metabolism with repercussions on growth during long-term thermal exposures.

The purpose of this study was to determine the effects of temperature on survival, moulting, and neuropeptide and mTOR signalling gene expression in the heart, Y-organ and eyestalk ganglia of the Dungeness crab, *Metacarcinus magister*. Juveniles from Northern California and Oregon experience temperatures ranging between 10 and 25°C (Brown and Terwilliger, 1999; Tasto, 1983). They moult successfully at 21°C, but growth is reduced compared with that at 14°C (Terwilliger and Dumler, 2001). We hypothesize that this pattern is reflected in temperature- and moult cycle-dependent expression of mTOR signalling components and neuropeptides in the tissues involved in moult regulation (eyestalk ganglia and Y-organ) and the heart of juvenile decapod crustaceans. The heart has been the subject of many ecophysiological studies with respect to thermal acclimation and adaptation owing to its central function in oxygen supply (Frederich et al., 2009; Stillman and Tagmount, 2009; Tepolt and Somero, 2014; Wittmann et al., 2012). We transferred naturally moulting juvenile *M. magister* from ambient conditions (~15°C) to six temperatures (5, 10, 15, 20, 25 and 30°C) for up to 14 days and monitored survival and moult stage progression. At the three temperatures that allowed moult progression (10, 15 and 20°C), mRNA levels were quantified by real-time RT-PCR of mTOR signalling components in the eyestalk ganglia, Y-organ and heart, and of the neuropeptides *Mm-CHH* and *Mm-MIH* in the eyestalk ganglia. There was a decrease in mRNA levels of certain mTOR signalling genes (e.g. *Mm-Rheb*) with increasing temperature, which may compensate for higher metabolic rates at higher temperature, in order to maintain consistent allocation of cellular energy to protein synthesis. As shown in previous studies of other decapod species, *Mm-Rheb* mRNA level can serve as a marker for Y-organ ecdysteroidogenic activity.

MATERIALS AND METHODS

Animals

Juvenile *Metacarcinus magister* (Dana 1852) were collected at the end of June 2013 from the lower intertidal of Bodega Harbor, CA, USA, using pitfall traps (Grosholz and Ruiz, 1995). Pitfall traps consisted of 20-litre buckets placed in the sediment to ground level. When crabs were collected after one tidal cycle (ca. 24 h), water temperatures in the traps ranged from 14 to 22°C. At the University of California, Davis, Bodega Marine Laboratory (BML), Bodega Bay, CA, USA, they were kept individually under a 12 h:12 h light:dark cycle in a flow-through system in trays with compartments of 7×7×11 cm with a mesh bottom and solid transparent plastic walls and lids at ambient water temperature. Ambient temperature was determined daily in one of the trays and ranged from 11 to 15°C until the experiment started in late August 2013, and usually was similar to BML ambient seawater temperature (data provided by BML; http://boon.ucdavis.edu/data_seawater_temperature.html). Salinity was 33–34 PSU (http://boon.ucdavis.edu/data_seawater_salinity.html). The crabs were cleaned and fed *ad libitum* with pieces of frozen squid three times per week. Moults were collected five days per week and carapace widths (CW) including the 10th anterolateral spines of the moults were determined to the nearest 0.01 mm using digital callipers. During maintenance at ambient temperature, most crabs moulted twice and grew in CW by approximately 30% with each moult. At the start of the experiment, CW was 42±4 mm and wet mass was 11±3 g for a total of 180 animals (means±s.d.), and moult interval ranged between 35 and 45 days owing to variation in size and ambient temperature.

Experimental design and sample collection

The recirculating incubation systems at 5, 10, 15, 20, 25 and 30°C each consisted of a water reservoir of 200–500 litres, individual glass jars of 470 ml (91 mm in diameter and 94 mm in height), which each housed one animal, and water tables that collected overflowing water from the jars and drained back into the reservoir tanks. The jars received water from the reservoir using a submersible aquarium pump (Eheim, Deizisau, Germany), a manifold and regular airline tubing at a flow rate of 400 ml min^{-1} at each outlet, and were covered with pieces of plastic light diffusion panels. All systems were equipped with air pumps and air stones, a temperature regulator (Pentair Aquatic Eco-Systems, Apopka, FL, USA) and up to three 300 W heaters (Eheim Jäger). Water was changed at least once per week to maintain water quality. The crabs were introduced and taken out for dissection in a staggered fashion, so that no more than 20 crabs were kept in each recirculating system at any time of

the 14 day incubation. To sample moult stages C to $D_{2–3}$, the experiment was started (t_0) with crabs at 12, 19 or 26 days postmoult, and tissues were collected from crabs at 26, 33 or 40 days postmoult at the end of the experiment (t_{14}). Only four sampled crabs moulted during the incubation period. Groups of 10 crabs each at 12 or 26 days postmoult at t_0 were incubated at 5°C, and groups of 10 crabs each at 12, 19 or 26 days postmoult were incubated at 10, 15, 20 or 25°C. An additional group of 10 crabs at 26 days postmoult was incubated at 10°C, and an additional group of 10 crabs at 19 days postmoult was incubated at 25°C. Two groups of 10 crabs at 19 days postmoult were incubated at 30°C, but died within hours, so crabs at 12 or 26 days postmoult were not tested. To minimize thermal shock during transfer, the 5, 25 and 30°C groups were first incubated for 2 h at each of the intermediate temperature steps, i.e. at 10 or 20°C and 25°C. We controlled for the sex ratio and size distribution in each of the temperature and days postmoult groups. We checked for moults and survival five days a week, and cleaned and fed *ad libitum* with pieces of squid mantle three times per week.

At t_0 and t_{14}, wet mass (g) and CW (mm) of the crabs were determined. Haemolymph samples were collected using needles and syringes (5 µl haemolymph immediately added to 50 µl dd H_2O) and stored at −20°C at both time points. Haemolymph ecdysteroid concentration was quantified with an enzyme-linked immunosorbent assay (ELISA) modified from Kingan (1989) and Tamone et al. (2007) as described in Abuhagr et al. (2014a). At t_0 and t_{14}, the basal endite of one of the third maxillipeds was excised and stored in crab saline and photographed under a microscope within 72 h to determine moult stage. Moult stage was determined after Drach and Tchernigoftzeff (1967) using illustrations of endites from Moriyasu and Mallet (1986), as well as haemolymph ecdysteroid concentrations [10–40 pg µl^{-1} in intermoult (C), 50–160 pg µl^{-1} in early premoult (D_0), 200–600 pg µl^{-1} in mid premoult (D_1), ≥1000 pg µl^{-1} in D_2, and a drop in ecdysteroids from D_3 onwards]. At t_{14}, 5–18 individuals per treatment group were dissected (total N=93, see Fig. S1), and the pairs of eyestalk ganglia and Y-organs, as well as 3–4 mm cubes of heart tissue, were stored in RNAlater (Life Technologies, Carlsbad, CA, USA) at 4°C overnight and then transferred to −20°C.

RNA isolation and cDNA synthesis

Pairs of eyestalk ganglia or Y-organs were hand-homogenized in 100 µl TRIzol reagent (Life Technologies, Carlsbad, CA, USA) using Kontes Pellet Pestle Grinders and 1.5 ml tubes (Kimble Chase, Vineland, NJ, USA). Heart tissues were homogenized with two 5 mm stainless steel balls (Abbott Ball Co., West Hartford, CT, USA) in precooled (−80°C) 2 ml tubes in a TissueLyzer II (Qiagen, Frederick, MD, USA) at 2×1 min at 30 Hz, then suspended in 1 ml of TRIzol reagent. After centrifugation for 15 min at 12,000 ***g*** at 4°C, total RNA was isolated from the supernatant. For eyestalk ganglia, the Direct-zol RNA MiniPrep kit with microcolumns (Zymo-Spin IC Column, Zymo Research, Irvine, CA, USA) was used according to the manufacturer's protocol with an in-column DNase I treatment including RNase inhibitor (RiboLock, Thermo Fisher Scientific, Waltham, MA, USA) for 30 min at 37°C. Total RNA of Y-organs and heart was extracted using the phenol-chloroform method as described in Covi et al. (2010). RNA purity and concentrations were determined by measuring absorbance at 260 and 280 mn using a NanoDrop 1000 Spectrophotometer (Thermo Fisher Scientific). Then, 400 ng of eyestalk ganglia RNA or 1 µg of Y-organ or heart RNA were reverse transcribed in 20 µl reactions using qScript cDNA SuperMix (Quanta Biosciences, Gaithersburg, MD, USA).

PCR cloning

Partial cDNAs encoding *M. magister Mm-AKT* (GenBank accession no. KT285226), *Mm-CHH* (KY070318), *Mm-Rheb* (KT315722), *Mm-mTOR* (KT315723), *Mm-S6K* (KT367806) and *Mm-AMPKα* (KT315720) were cloned using nested specific or degenerate primers and RNA ligase mediated rapid amplification of cDNA ends (RLM-RACE). Primers (Table S1; Integrated DNA Technologies, Coralville, IA, USA) were designed to bind to highly conserved regions, as identified by multiple sequence alignment including a suite of pancrustacean and vertebrate species. Sequences were aligned using Clustal X (http://www.clustal.org/clustal2/) and GeneDoc software (http://iubio.bio.indiana.edu/soft/molbio/ibmpc/genedoc-readme.html). Template cDNA from eyestalk ganglia, Y-organ, heart, claw or thoracic muscle was used for initial PCR reactions, which consisted of 1 µl cDNA, 1 µl forward and 1 µl reverse primer (10 µmol l^{-1}), 5 µl 2× PCR mastermix (Thermo Fisher Scientific) and 2 µl nuclease-free water. 3′ RACE was performed with the FirstChoice RLM-RACE kit (Life Technologies, Carlsbad, CA, USA) according to the manufacturer's protocol, except PCR reactions consisted of 1 µl cDNA, 2 µl gene-specific forward primer and 2 µl reverse primer (10 µmol l^{-1}, from RLM-RACE kit), 25 µl 2× PCR mastermix (Thermo Fisher Scientific) and 20 µl nuclease-free water. The PCR was carried out using a Veriti 96 Well Thermal Cycler (Applied Biosystems, Foster City, CA, USA) with an initial denaturation for 4 min at 96°C, followed by 35 cycles of denaturation for 30 s at 94°C, annealing at the respective melting temperature of the primers for 30 s, and elongation for 30–120 s at 72°C, depending on the expected product length (1000 bp min^{-1}). Final elongation for 7 min occurred at 72°C, followed by a hold at 4°C.

Products were separated on a 1.0% agarose gel in TAE buffer for 90 min at 100 V, stained with ethidium bromide and extracted using the Qiaex II Gel Extraction kit (Qiagen, Valencia, CA, USA). Sequencing was carried out by Davis Sequencing (Davis, CA, USA) using the respective primers that yielded the products.

Quantitative real-time PCR

Roche LightCycler 480 and LightCycler Fast Start DNA Master PLUS SYBR Green I reaction mix (Roche Applied Science, Penzberg, Germany) were used to quantify absolute mRNA levels of *Mm-AKT*, *Mm-Rheb*, *Mm-mTOR*, *Mm-S6K*, *Mm-AMPKα*, *Mm-CHH*, *Mm-MIH* (GenBank accession no. AF031493; Umphrey et al., 1998) and *Mm-RbS3* (ribosomal protein S3; JF276909.1; Martin et al., 2011; previously used as reference gene). Reactions were combined on 384-well plates and consisted of 1 µl cDNA template, standard, no reverse transcriptase control or negative control (nuclease-free water), 0.5 µl (10 µmol l^{-1}) gene-specific forward and reverse primers (Table 1), 5 µl 2× SYBR Green master mix and 3 µl nuclease-free water. PCR conditions were 3 min at 95°C for initial denaturation, then 45 cycles of 30 s at 95°C, 30 s at the primer annealing temperatures (Table 1) and 20 s at 72°C for elongation, followed by 7 min at 72°C for final extension. Melting curves and crossing point (C_p) values were determined using Roche LightCycler 480 Software version 1.5.0 SP4. Absolute mRNA levels (copies µg^{-1} RNA) were calculated from the respective standard curves ranging from 10^{-10} to 10^{-18} g µl^{-1} of purified cDNA product of each gene (see Table 1 for primers; see 'PCR cloning' above for PCR conditions and product purification).

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

Table 1. Primers for quantitative real-time PCR of the respective genes, annealing temperatures (°C), product lengths (bp) and references

Primer name	Sequence 5′ ->3′	Annealing temperature (°C)	Product length (bp)	Reference
Mm-AKT F2	CCAGGAGGTCAGTTCGGTGG	62	252	Present study
Mm-AKT R2	AGCGTATGGGCCACCTCATC			
Ci-AMPKα qF1	TCCGCAAGATTAAGTCGGGTGTGT	60	117	Frederich et al., 2009
Ci-AMPKα qR1	TATCCTCAATGGTGGCTCGCTTCA			
Mm-CHH qF2	GAGCACGTGTGTGACGATTG	55	177	Present study
Mm-CHH qR2	TGTTTACTTCTTCCTGCCAACCATC			
Mm-MIH F1	ACGACGACTGTCCAAACCTTA	55	242	Umphrey et al., 1998
Mm-MIH R1	GATAACCTTGTTGACTCACTC			
Mm-mTOR qF1	TGTTACGGATGGCACAGGAC	60	170	Present study
Mm-mTOR qR1	CAGTGAGCGGGAGTAGTTGG			
Mm-RbS3 F1	CAAGGCCAAACTCAACAGGTTC	55	139	Martin et al., 2011
Mm-RbS3 R1	GTCCCTTTTCACCAAGGACA			
Mm-Rheb qF1	CACCTGGAGCGTGTAGTG	60	207	Present study
Mm-Rheb qR1	GGTTGTGGCTATATCACAGAGT			
Mm-S6K F1	ACGCCTTTCAAACGGGAGGG	62	296	Present study
Mm-S6K R2	CTCAATGGTGCCGCAGAACG			

Primers are prefixed with species names: *Ci*, *Cancer irroratus*; *Mm*, *Metacarcinus magister*.

Data are presented as $\log_2$(fold expression) relative to the mean absolute mRNA level at stage C at 15°C (Table 2).

Data analysis and statistics

Statistical analyses were carried out using GraphPad Prism Version 7.0b (GraphPad Software, La Jolla, CA, USA). The Mantel–Cox test was used to test effects of temperature on survival. Moult progression is presented only for animals in D_0 at t_0 as t_{14}/t_0 ratios of ecdysteroid concentration and as progression from D_0 to D_1 or $D_{2–3}$. Ecdysteroid concentrations and their ratios were $\log_{10}$ transformed to fulfil the prerequisite of equal variances. Because moult stage of the individuals at a given day postmoult was variable at both t_0 and t_{14} at all temperatures (Fig. S1), qPCR data were grouped by moult stage rather than by days postmoult. qPCR data from 5°C-incubated animals were excluded from the analysis, as no data or not enough data were available from animals in mid and late premoult (D_1 and $D_{2–3}$). Factorial changes in absolute mRNA levels relative to the mean absolute mRNA levels at stage C at 15°C were $\log_2$ transformed. Outliers were detected using the ROUT test, and removed. Subsequently, one-way or two-way ANOVA and the *post hoc* Tukey multiple comparisons test were used to test for significant effects of temperature and moult stage at the $P<0.05$ level. Pearson correlation coefficients (r) and goodness of fit of linear regressions (R^2) were determined for relationships between $\log_{10}$-transformed ecdysteroid concentrations and *Mm-Rheb* mRNA levels. An ANCOVA was used to compare the slopes and y-intercepts of the regression lines.

RESULTS

Effects of temperature on survival and moult progression

Temperature affected survival ($P<0.0001$). At 30°C, all animals died within 24 h (Fig. 1). At 25°C, animals started dying after 3 days, with only 48% of the animals surviving after 7 days and 0% surviving after 14 days. Survival was 100% at 5 and 15°C, and 98% and 97% at 10 and 20°C, respectively, over the 14-day incubation period.

Table 2. Results of two-way ANOVA of $\log_2$-transformed *x*-fold gene expression relative to stage C at 15°C in eyestalk ganglia, Y-organ and heart of juvenile *Metacarcinus magister* incubated at the respective temperatures for 14 days (Figs 4–6)

Tissue	Gene *Mm-*	Absolute expression (copies µg^{-1} RNA) means±s.e.m., stage C 15°C	Temperature		Moult stage		Interaction	
			F	*P*	*F*	*P*	*F*	*P*
Eyestalk ganglia	*AKT*	$1.0±0.1×10^7$	54.3	**<0.0001**	2.8	**0.0497**	2.2	0.0593
	AMPKα	$2.1±0.2×10^6$	35.3	**<0.0001**	1.4	0.2442	1.9	0.1006
	CHH	$2.6±0.2×10^7$	13.4	**<0.0001**	0.9	0.4556	2.1	0.0697
	MIH	$1.4±0.2×10^7$	30.2	**<0.0001**	5.2	**0.0028**	2.7	**0.0208**
	Rheb	$5.7±0.7×10^5$	140.3	**<0.0001**	0.8	0.4796	1.6	0.1622
	S6K	$3.6±0.4×10^6$	8.2	**0.0007**	3.4	**0.0238**	0.8	0.5729
Y-organ	*AKT*	$2.9±0.5×10^6$	10.0	**0.0002**	4.0	**0.0109**	0.6	0.7074
	AMPKα	$7.7±1.2×10^5$	0.9	0.4117	3.5	**0.0203**	1.1	0.3806
	mTOR	$2.7±0.2×10^4$	6.4	**0.0029**	4.5	**0.0067**	0.8	0.5842
	RbS3	$2.5±0.3×10^5$	4.5	**0.0152**	1.9	0.1422	0.7	0.6841
	Rheb	$2.5±0.4×10^5$	30.1	**<0.0001**	17.3	**<0.0001**	0.3	0.2483
	S6K	$1.1±0.2×10^6$	3.0	**0.0383**	4.8	**0.0047**	1.0	0.4558
Heart	*AKT*	$2.2±0.2×10^6$	8.4	**0.0006**	3.9	**0.0138**	0.7	0.6222
	AMPKα	$5.4±0.7×10^5$	6.6	**0.0026**	1.9	0.1358	1.3	0.2742
	mTOR	$4.2±0.6×10^5$	3.5	**0.0384**	0.4	0.7327	3.4	**0.0066**
	RbS3	$4.3±0.5×10^5$	1.0	0.3840	2.3	0.0824	0.5	0.8094
	Rheb	$1.7±0.1×10^5$	66.7	**<0.0001**	5.6	**0.0020**	0.7	0.6546
	S6K	$7.2±0.7×10^5$	13.5	**<0.0001**	2.9	**0.0432**	1.4	0.2325

Significance at $P<0.05$ in bold.

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

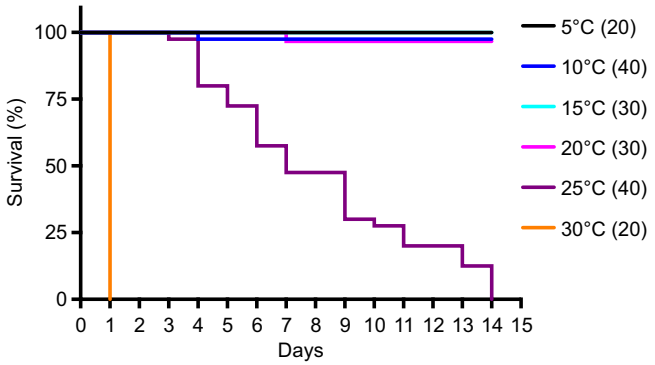

Fig. 1. Survival of *Metacarcinus magister* juveniles during 14 days of incubation at temperatures ranging from 5 to 30°C. Survival curves were significantly different (Mantel–Cox test, $P<0.05$). Sample size (N) is given in parentheses.

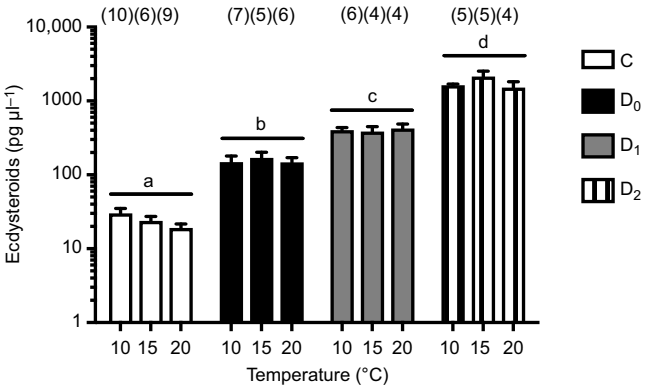

Fig. 3. Haemolymph ecdysteroid concentrations (pg µl^{-1}) of juvenile *M. magister* in intermoult (C, white), early (D_0, black), mid (D_1, grey) or late (D_2, striped) premoult after 14 days of incubation at 10, 15 or 20°C (t_{14}). Results of two-way ANOVA of $\log_{10}$-transformed data: temperature: $F=0.7$, $P=0.4991$, moult stage: $F=325.7$, $P<0.0001$, interaction: $F=0.7$, $P=0.6253$; different letters denote significant differences according to the Tukey *post hoc* test at $P<0.05$. Sample size (N) is given in parentheses; animals in D_3 were excluded from the graph and statistical analysis. Data are presented as means±s.e.m. Note the logarithmic y-axis.

Moult progression increased with temperature. Among the group of animals in D_0 at t_0, individuals tested at 5°C did not progress in the moult cycle within the observation period, whereas the crabs incubated at 10, 15 or 20°C did so (Fig. 2). Most animals at 10, 15 or 20°C exhibited t_{14}/t_0 ecdysteroid ratios greater than 1, resulting in significantly higher means than the animals at 5°C ($F=0.54$, $P<0.0001$; Fig. 2A). Consequently, all the D_0 animals incubated at 5°C remained in this stage (Fig. 2B), while at 10°C, 43% remained in D_0 and 57% progressed to D_1. At 15°C, almost half of the animals (46%) advanced to $D_{2–3}$, while 23% remained in D_0 and 31% progressed to D_1. At 20°C, 27% of the animals remained in D_0, while 36% progressed to D_1 and 36% progressed to $D_{2–3}$ by 14 days.

At t_{14}, haemolymph ecdysteroid levels of all the individuals incubated at 10, 15 or 20°C varied by moult stage ($P<0.0001$), but not by temperature (Fig. 3). Ecdysteroid concentrations increased significantly from moult stage to moult stage in each temperature group and were approximately 100-fold higher in stage D_2 compared with stage C. In intermoult, ecdysteroid titres varied from 19±3 pg µl^{-1} at 20°C to 28±5 pg µl^{-1} at 10°C. In stage D_0, values increased to 147±32 pg µl^{-1} at 10°C, 169±34 pg µl^{-1} at 15°C and 146±25 pg µl^{-1} at 20°C. In D_1, titres ranged from 383±68 pg µl^{-1} at 15°C to 420±65 pg µl^{-1} at 20°C. Maximal concentrations at stage D_2 ranged from 1506±318 pg µl^{-1} at 20°C to 2123±403 pg µl^{-1} at 15°C.

Effects of temperature and moult stage on mRNA levels

Eyestalk ganglia

mRNA levels in eyestalk ganglia were significantly affected by temperature, with a general trend of being higher at 10°C and/or lower at 20°C (Fig. 4, see Table 2 for results of two-way ANOVA). *Mm-MIH*, *Mm-AKT* and *Mm-S6K* were also significantly affected by moult stage. Only for *Mm-MIH* was a significant interaction observed between temperature and moult stage. *Mm-RbS3* and *Mm-mTOR* were not included in the analysis because a reliable quantification was not possible owing to low mRNA levels and residual genomic DNA.

Mm-Rheb was upregulated up to 2.2-fold between 15 and 10°C in all moult stages (P ranged from <0.0001 in C to 0.0033 in $D_{2–3}$, Tukey *post hoc* test; Fig. 4A), downregulated in stage C by 0.6-fold between 20 and 15°C ($P=0.0036$) and downregulated by 0.3-fold

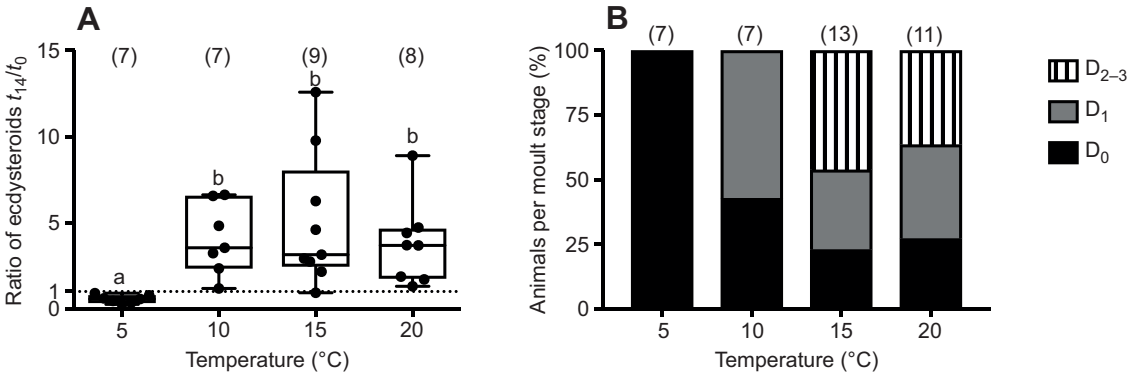

Fig. 2. Progression of the moult cycle through early premoult (D_0) in juvenile *M. magister* is dependent on temperature. (A) Ratio of haemolymph ecdysteroid concentrations (t_{14}/t_0). $t_{14}/t_0<1$ and $t_{14}/t_0=1$ indicate no progression of the moult cycle, $t_{14}/t_0>1$ indicates progression of the moult cycle. One-way ANOVA of $\log_{10}$-transformed data: $F=16.4$, $P<0.0001$. Different letters denote significant differences according to the Tukey *post hoc* test at $P<0.05$. Boxes represent medians and the interquartile range, error bars minimum to maximum values. (B) Percentage of animals that remained in early premoult (stage D_0; black) or progressed to mid (D_1; grey) or late premoult ($D_{2–3}$; striped) at t_{14}. Sample size (N) is given in parentheses. Only the subgroup of animals in D_0 at t_0 was used for this graph. See Fig. S1 for progression through other moult stages. Data pairs with unreasonably high ecdysteroid concentrations at D_0 (ELISA out of range), animals in D_3 (drop of ecdysteroids) and an outlier at 20°C were excluded from A but retained for B.

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

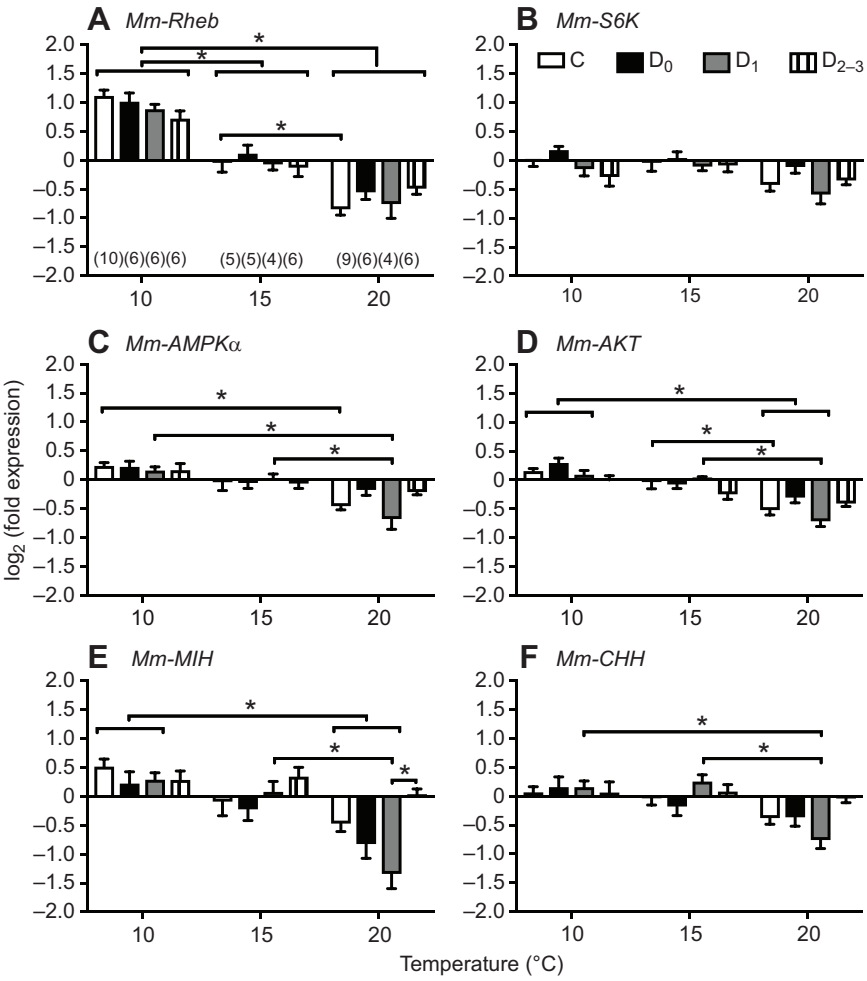

Fig. 4. mRNA levels in eyestalk ganglia after 14 days of incubation at 10, 15 or 20°C of *M. magister* juveniles in intermoult (C, white), early (D_0, black), mid (D_1, grey) or late ($D_{2–3}$, striped) premoult. (A) *Mm-Rheb*, (B) *Mm-S6K*, (C) *Mm-AMPKα*, (D) Mm-AKT, (E) Mm-MIH and (F) *Mm-CHH*. Data are normalized to the mean absolute mRNA levels in stage C at 15°C (Table 2). For results of two-way ANOVA, see Table 2; for results of the *post hoc* Tukey test, see Results. Asterisks denote significant differences according to the Tukey *post hoc* test at $P<0.05$. Sample size (N) is given in parentheses in A also applies to the other genes; data are presented as means±s.e.m.

between 10 and 20°C ($P<0.0001$). In the other moult stages, the differences between 15 and 20°C were not significant, but the differences between 10 and 20°C were all highly significant (0.3- to 0.4-fold, $P<0.0001$). There were no significant differences in *Mm-S6K* levels in *post hoc* comparisons of biological interest (Fig. 4B). *Mm-AMPKα* levels differed in stage C and D_1 between 10 and 20°C (both by 0.6-fold, $P<0.0001$, Tukey test; Fig. 4C) and in stage D_1 also between 15 and 20°C (0.6-fold, $P=0.0069$). *Mm-AKT* differed between 15 and 20°C in stages C ($P=0.0042$; Fig. 4D) and D_1 ($P=0.0002$), and between 10 and 20°C in stages C to D_1 ($P<0.0001$, $P=0.0005$, $P<0.0001$, 0.6-fold).

Mm-MIH levels decreased in stage C animals 0.5-fold between 10 and 20°C ($P=0.0007$, Tukey test; Fig. 4E). In stage D_1, *Mm-MIH* levels at 20°C were lower than at 10 and 15°C ($P<0.0001$ and $P=0.0019$, 0.3-fold). At 20°C, *Mm-MIH* was upregulated by a factor of 2.5 from stages D_1 to $D_{2–3}$ ($P=0.0008$). Although the trends in *Mm-CHH* levels were similar to those in *Mm-MIH* levels, the differences were smaller as no upregulation occurred upon exposure to 10°C (Fig. 4F). In stage D_1, *Mm-CHH* levels at 20°C were lower than at 10°C ($P=0.0067$, Tukey test) and at 15°C ($P=0.0057$), both by 0.5-fold.

Y-organs

In the Y-organ, *Mm-Rheb*, *Mm-AKT*, *Mm-AMPKα*, *Mm-mTOR* and *Mm-S6K* were significantly affected by moult stage, and *Mm-Rheb*, *Mm-AKT*, *Mm-mTOR*, *Mm-S6K* and *Mm-RbS3* were significantly affected by temperature (ANOVA; Fig. 5, Table 2). There was no significant interaction between moult stage and temperature in any of the genes. When affected by temperature, mRNA levels decreased with increasing temperature. For *Mm-Rheb* (Fig. 5A), *Mm-S6K* (Fig. 5B) and *Mm-AMPKα* (Fig. 5C), there was a trend for an increase with progressing moult stages. For *Mm-AKT* (Fig. 5D) and *Mm-mTOR* (Fig. 5E), there was a trend for higher mRNA levels in stages D_0 and D_1 compared with stages C and $D_{2–3}$.

Mm-Rheb mRNA levels were lower at 20°C compared with 10°C in stages C and D_0 by 0.4-fold ($P<0.0001$ and $P=0.0050$, Tukey *post hoc* test; Fig. 5A), and in stage C at 15°C compared with 20°C ($P=0.0111$, 0.5-fold). At 10°C, mRNA levels were elevated by a factor of 1.8 in stage D_1 compared with stage C ($P=0.0389$). At 20°C, *Mm-Rheb* levels increased from stage C to D_1 and $D_{2–3}$ (2.4- and 3.0-fold, $P=0.0028$ and $P<0.0001$). *Mm-AKT* levels were lower at 20°C compared with 10°C in stage C (0.6-fold, $P=0.0435$, Tukey test; Fig. 5D). There were no significant differences in *Mm-S6K* (Fig. 5B), *Mm-AMPKα* (Fig. 5C), *Mm-mTOR* (Fig. 5E) or *Mm-RbS3* (Fig. 5F) mRNA levels in *post hoc* comparisons of biological interest.

Heart

In the heart, the mRNA levels of all genes except *Mm-RbS3* were significantly affected by temperature, and the mRNA levels of *Mm-Rheb*, *Mm-AKT* and *Mm-S6K* also varied with moult stage (ANOVA; Fig. 6, Table 2). There was a significant interaction between moult stage and temperature in *Mm-mTOR* mRNA levels.

In all moult stages, *Mm-Rheb* mRNA levels at 15 and 20°C were lower than at 10°C ($P<0.0001$ to $P=0.0285$, Tukey test; Fig. 6A).

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

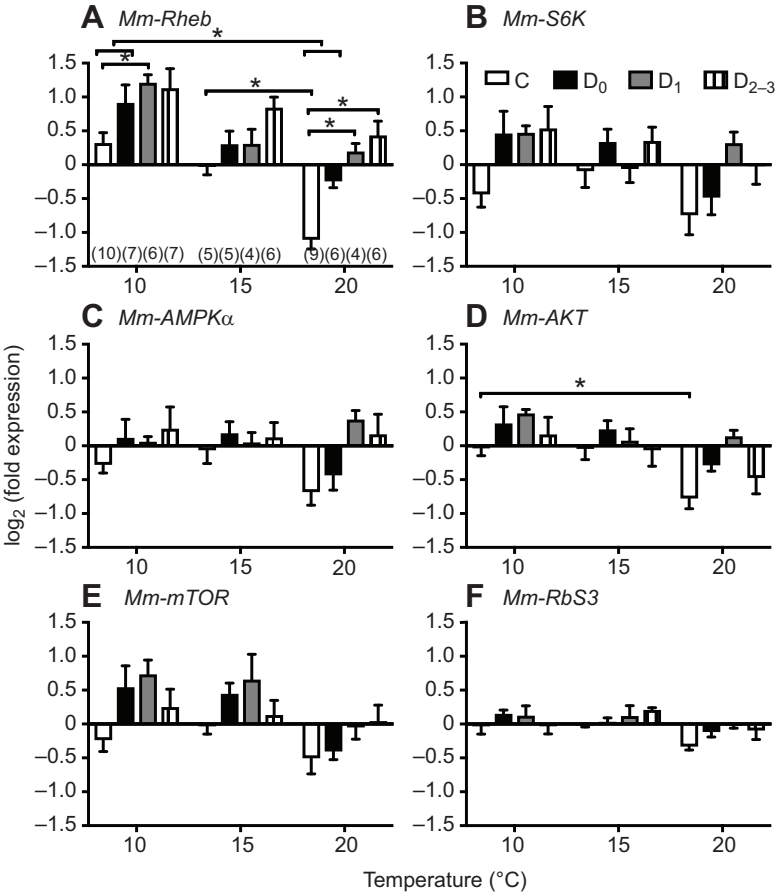

Fig. 5. mRNA levels in Y-organ after 14 days of incubation at 10, 15 or 20°C of *M. magister* juveniles in intermoult (C, white), early (D_0, black), mid (D_1, grey) or late ($D_{2–3}$, striped) premoult. (A) *Mm-Rheb*, (B) *Mm-S6K*, (C) *Mm-AMPKα*, (D) *Mm-AKT*, (E) *Mm-mTOR* and (F) *Mm-RbS3*. Data are normalized to the mean absolute mRNA levels in stage C at 15°C (Table 2). For results of two-way ANOVA, see Table 2; for results of the *post hoc* Tukey test, see Results. Asterisks denote significant differences according to the Tukey *post hoc* test at $P<0.05$. Sample size (N) is given in parentheses in A also applies to the other genes; data are presented as means±s.e.m.

Factorial change ranged among the moult stages from 0.3 to 0.4 between 10 and 15°C and from 0.2 to 0.3 between 10 and 20°C. The latter were the largest fold changes found by this study; in other words, a 5.3-fold increase at a temperature decrease from 20 to 10°C in stage D_1. Although not identified by the *post hoc* test, it is noteworthy that there was a trend for reduced *Mm-Rheb* mRNA levels with progression of the moult cycle by up to 0.5 at 20°C. The mRNA levels of the kinases *Mm-S6K* (Fig. 6B), *Mm-AMPKα* (Fig. 6C), *Mm-AKT* (Fig. 6D) and *Mm-mTOR* (Fig. 6E) varied little and exhibited similar patterns. There were differences only in *Mm-S6K* between 10 and 15°C in stage C ($P=0.0360$, 0.6-fold, Tukey test; Fig. 6B) and in *Mm-mTOR* between 10 and 20°C in stage C ($P=0.0018$, 0.6-fold; Fig. 6E).

Relationship between haemolymph ecdysteroid and *Mm-Rheb* levels

In eyestalk ganglia, the correlation between $\log_{10}$ ecdysteroids and *Mm-Rheb* copies μg^{-1} RNA varied with temperature (Fig. 7A, see Table S2 for statistics). There was a negative correlation at 10°C ($P=0.0420$), no correlation at 15°C and a positive correlation at 20°C ($P=0.0159$). Consequently, there were differences in the slopes of the regression lines ($F=4.758$, $P=0.0118$). Given that the slopes differed greatly, it was not possible to determine whether the elevations differed significantly. Goodness of linear fits (R^2) varied between 0.00646 (15°C) and 0.2367 (20°C).

In the Y-organ, a positive correlation of the two variables was highly significant at all temperatures (P between 0.0081 and <0.0001; Fig. 7B, Table S2). The slopes of the lines did not differ significantly ($F=0.1279$, $P=0.8802$), but the difference between the elevations was highly significant ($F=23.78$, $P<0.0001$), which indicates an inverse relationship between *Mm-Rheb* mRNA levels and temperature. R^2 ranged from 0.2322 (10°C) to 0.7008 (20°C).

In the heart, $\log_{10}$ ecdysteroids and *Mm-Rheb* levels were negatively correlated (10°C: $P=0.0498$; 20°C: $P=0.0004$) or not correlated (15°C; Fig. 7C, Table S2). There was no significant difference between the slopes of the fitted lines ($F=1.182$, $P=0.3136$), but there was a significant difference between the elevations of the lines ($F=51.66$, $P<0.0001$), indicating higher *Mm-Rheb* mRNA levels at 10°C. R^2 varied between 0.0855 (15°C) and 0.491 (20°C).

DISCUSSION

Summer water temperatures in the intertidal of embayments and estuaries of Northern California and Oregon vary between 10 and 25°C (Brown and Terwilliger, 1999; Tasto, 1983), and we observed a maximum of 22°C when collecting juveniles from Bodega Harbor during summer 2013. Larval and juvenile *M. magister* from different locations along the North Pacific coast show high survival and decreasing moult interval from 5 to 18°C, and stagnating moulting frequency and growth at higher temperatures (Brugman, 1972; Kondzela and Shirley, 1993; Sulkin and McKeen, 1989; Sulkin et al., 1996; Terwilliger and Dumler, 2001). This is consistent with our results on temperature-dependent survival and moult progression (Figs 1 and 2). Oxygen consumption rate increases up to 3-fold in *M. magister* between 10 and 20°C, resulting in extraordinarily high Q_{10} values (Brown and Terwilliger, 1999; Gutermuth and Armstrong, 1989; McLean and Todgham, 2015; Prentice and Schneider, 1979). At 20°C, metabolic maintenance costs may become so high that energy partitioned for growth is reduced (Pörtner and Knust, 2007; Pörtner, 2010;

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

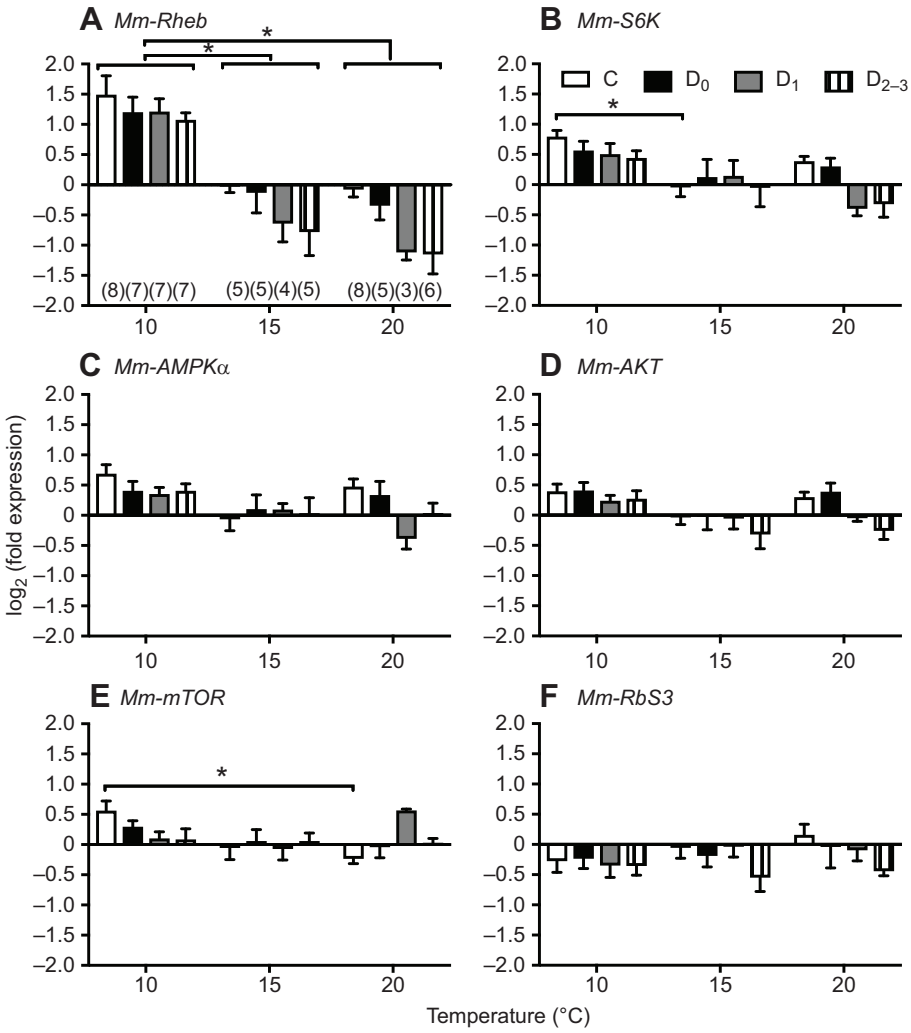

Fig. 6. mRNA levels in heart after 14 days of incubation at 10, 15 or 20°C of *M. magister* juveniles in intermoult (C, white), early (D_0, black), mid (D_1, grey) or late ($D_{2–3}$, striped) premoult. (A) *Mm-Rheb*, (B) *Mm-S6K*, (C) *Mm-AMPKα*, (D) *Mm-AKT*, (E) *Mm-mTOR* and (F) *Mm-RbS3*. Data are normalized to the mean absolute mRNA levels in stage C at 15°C (Table 2). For results of two-way ANOVA, see Table 2; for results of the *post hoc* Tukey test, see Results. Asterisks denote significant differences according to the Tukey *post hoc* test at $P<0.05$. Sample size (N) is given in parentheses in A also applies to the other genes; data are presented as means±s.e.m.

Sokolova et al., 2012; Terwilliger and Dumler, 2001). Thus, higher metabolic rate does not translate into faster moult progression, and the crabs seem to have reached or surpassed a maximum rate for completing premoult processes. Juvenile survival is only compromised at substantially longer exposures to this temperature than in the present study and at higher temperatures (Brugman, 1972; Kondzela and Shirley, 1993; Sulkin and McKeen, 1989; Sulkin et al., 1996; Terwilliger and Dumler, 2001).

In the temperature range 10 to 20°C, haemolymph ecdysteroid levels throughout the moult cycle of the juveniles were similar to those of adult *M. magister* (Fig. 3; Thomton et al., 2006). In the lobster *Homarus americanus*, temperature-dependent regulation of ecdysteroid titers is necessary to prevent premature (i.e. lethal) moults (Aiken and Waddy, 1975; Chang and Bruce, 1980). In the copepod *Calanus pacificus*, ecdysteroid titers decrease with lower temperatures (Johnson, 2003). It is possible that low temporal

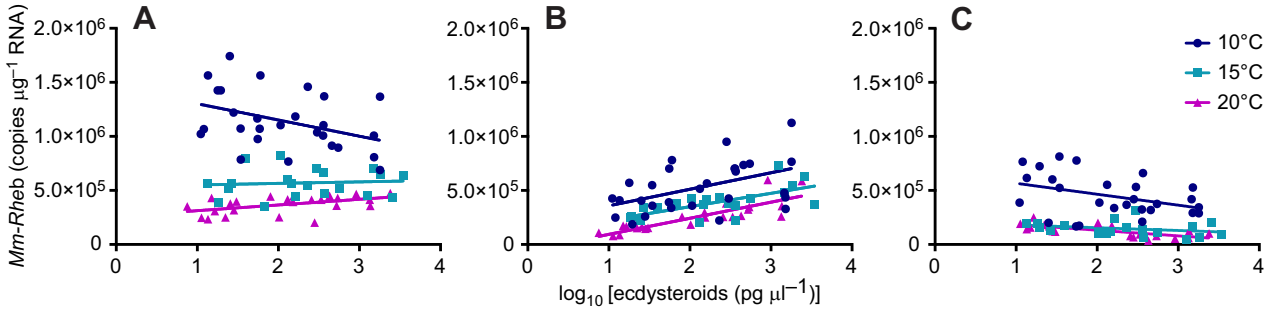

Fig. 7. Relationship between $\log_{10}$-transformed circulating ecdysteroid levels (pg µl^{-1}) and *Mm-Rheb* expression (copies µg^{-1} RNA) in juvenile *M. magister* after 14 days incubation at 10°C (dark blue circles), 15°C (light blue squares) or 20°C (pink triangles) throughout the moult cycle. (A) Eyestalk ganglia, (B) Y-organ and (C) heart. *Mm-Rheb* expression as also presented in Figs 4–6 as $\log_2$-transforms of factorial change, excluding two *x*–*y* pairs of late premoult (D_3) animals with ecdysteroids below the detection limit of the ELISA. For sample size (N), see Figs 4–6. For goodness of fit of linear regression (R^2), Pearson correlation coefficients (r) and P-values, see Table S2.

resolution precluded detection of temperature-dependent differences in ecdysteroid titre in our study. Alternatively, similar ecdysteroid concentrations at 10, 15 and 20°C in juvenile *M. magister* may result from the active regulation of both biosynthesis and degradation/elimination of moulting hormone (Mykles, 2011).

In most decapods, the neuropeptide MIH appears to be regulated post-transcriptionally over the normal moult cycle, as *MIH* mRNA levels in the eyestalk ganglia can remain elevated during premoult (Chung and Webster, 2003, 2005; Covi et al., 2012; Pitts and Mykles, 2017; Techa et al., 2015; Techa and Chung, 2015). Genetic manipulation of *Rheb* and other mTOR components in insects highlights the importance of this pathway for protein synthesis (Danielsen et al., 2016; Hall et al., 2007; Parthasarathy and Palli, 2011). In *Drosophila melanogaster*, inhibition of mTORC1 in neurosecretory brain cells that produce prothoracicotropic hormone, which stimulates ecdysteroid production in the prothoracic gland, did not alter the timing of pupariation (Layalle et al., 2008). Thus, mTORC1 does not seem to be necessary for the control of neurohormone expression, synthesis, and/or secretion in insects under normal conditions. However, environmental stressors or conditions may inhibit moulting by upregulating *MIH* expression, thus maintaining high circulating MIH levels that prevent Y-organ activation. For example, some *G. lateralis* individuals fail to moult in response to multiple leg autotomy, indicating the animals are in a blocked or chronically inhibited condition (Pitts et al., 2017). The eyestalk ganglia of blocked animals exhibit 200- to 400-fold higher mRNA levels of *Gl-MIH*, *Gl-CHH* and three of four mTOR components, including *Gl-Rheb*, than the eyestalk ganglia from control animals (Pitts et al., 2017). These data suggest that mTOR signalling enhances neuropeptide production in eyestalk ganglia of animals with an activated Y-organ to prevent or delay moulting under adverse conditions.

Our study provides important insights into the role of mTOR signalling in the eyestalk ganglia of juvenile *M. magister*. In the thermal range that allows moult progression, transcriptional regulation of *Mm-Rheb* may contribute to the control of neuropeptide synthesis in response to temperature rather than over the moult cycle. The significant interaction term in *Mm-MIH* mRNA levels indicates that moulting is regulated differently at different temperatures. At temperatures that juvenile *M. magister* tolerate over prolonged periods (10 and 15°C; Kondzela and Shirley, 1993), *Mm-MIH* was constitutively expressed over the moult cycle, as expected. A decrease of *MIH* expression in premoult was reported for *Callinectes sapidus* and in *Scylla paramamosain* (Huang et al., 2015; Lee et al., 1998) and observed in our experimental animals at 20°C. Transcription was downregulated at 20°C also in the other genes, but to a lesser extent. Unlike at lower temperatures, at 20°C, *M. magister* juveniles control MIH transcriptionally, yet with a time lag. *Mm-MIH* mRNA levels were reduced by about half from stages C to D_1 (Fig. 4E), which is when the committed Y-organ becomes least sensitive to MIH through the end of premoult (Chang and Mykles, 2011). In stage $D_{2–3}$, *Mm-MIH* recovered by a factor of 2.5, which would allow the eyestalk ganglia to resume a greater rate of MIH synthesis in preparation for MIH release during postmoult and intermoult. Consistent with this, Techa and Chung (2015) found a time lag between transcription and peptide storage in *C. sapidus* eyestalk ganglia in premoult. Owing to the variable correlation coefficients between ecdysteroid concentration and *Mm-Rheb* expression in eyestalk ganglia, a (simple) feedback mechanism of ecdysteroid on neuropeptide production (Techa and Chung, 2015) via mTOR seems unlikely. However, transcriptional compensation of mTOR components and neuropeptides may counteract temperature-dependent effects on neuropeptide synthesis, as hypothesized for moderate thermal stress.

mTOR-dependent protein synthesis is required for increased ecdysteroid synthesis and secretion in the activated Y-organ. Transcriptional regulation of this pathway takes place not only during moult induction in *G. lateralis* (Abuhagr et al., 2014b, 2016; Das et al., 2018; Shyamal et al., 2018), but also during naturally occurring moults in *M. magister*. However, the expression patterns differ between species (no change to up to 10-fold change), and differing degrees of post-transcriptional regulation are likely (Abuhagr et al., 2014b; 2016). In *M. magister*, *Mm-Rheb* increased up to 3-fold from intermoult to late premoult, while gene expression changes of the protein kinases mTOR, AMPK, AKT and S6K were smaller, yet significant (Fig. 5). The positive correlations between *Mm-Rheb* mRNA levels and ecdysteroid titres at all three temperatures support the role of this GTPase in the regulation of the moult cycle through the mTOR pathway (Fig. 7B). As mTORC1 is a direct target of Rheb (Long et al., 2005), *Mm-Rheb* may serve as a proxy for mTOR activity as a function of temperature and moult stage in the Y-organ of *M. magister*. Adjusting *Mm-Rheb* in the Y-organ to higher levels in the cold and lower levels in the warmth may play an important role in coping with moderate thermal stress.

AMPK was the only protein kinase in the Y-organ not significantly affected by temperature. Keeping a certain level of *Mm-AMPKα*, especially in mid and late premoult, would maintain regulatory capacity and, at least to some extent, may help in the downregulation of metabolic cost by phospho-AMPK at 20°C. Partial inhibition of protein synthesis in the warmth may contribute to similar ecdysteroid levels across temperatures. In addition, taking into account the expression of the activating mTOR components, a 1.9-fold increase in *Mm-AMPKα* from intermoult to late premoult at 20°C may counterbalance the 3.0- and 1.6-fold increases of *Mm-Rheb* and *Mm-S6K*, respectively. At 10°C, by contrast, a relatively small increase in *Mm-AMPKα* (1.6-fold) opposes larger changes of *Mm-Rheb* (1.9-fold), *Mm-S6K* (2.1-fold) and *Mm-mTOR* (1.9-fold) throughout the moult cycle. This may promote protein synthesis and thereby ecdysteroid production at thermally reduced kinetic energy. Posttranscriptional regulation of the kinases, e.g. through phosphorylation by upstream kinases, may play an important role in the regulation of the mTOR pathway in the Y-organ, and needs to be studied in the future.

Tissue- and fibre-specific regulation of protein turnover through the mTOR pathway contributes to regulating muscle growth (Bodine et al., 2001; Goodman et al., 2011; Saxton and Sabatini, 2017), cardiac homeostasis and compensatory cardiomyocyte growth in mammals (reviewed in Sciarretta et al., 2014). In crustaceans, muscle protein synthesis and ribosomal activity are higher in premoult than in postmoult and intermoult, and are regulated by ecdysteroid and other factors (El Haj et al., 1996; reviewed in Mykles and Medler, 2015). mTOR signalling components, especially *Rheb*, are upregulated in atrophic claw muscle of *G. lateralis* during premoult after moult induction (MacLea et al., 2012) and in naturally moulting *Carcinus maenas* (Cosenza, 2016). Thus, mTOR activation may relate to increased protein turnover during claw muscle atrophy, which facilitates the passage of the tissue through the narrow joint (Covi et al., 2010; MacLea et al., 2012; reviewed in Mykles and Medler, 2015). There is a significant positive correlation between haemolymph ecdysteroid concentrations and *Rheb* expression in claw muscle, but no correlation in thoracic muscle (Cosenza, 2016; MacLea et al.,

Journal of Experimental Biology (2018) 221, jeb187492. doi:10.1242/jeb.187492

2012). We found no correlation (at 15°C) or negative correlations (at 10 and 20°C) between *Mm-Rheb* in the heart and ecdysteroid titres of *M. magister* juveniles (Fig. 7C). Consistent with this, actin and myosin protein content decrease from intermoult to premoult at constant soluble protein and water content in abdominal muscle of juvenile shrimp (de Oliveira Cesar et al., 2006). mRNA levels of muscle proteins exhibit a similar pattern over the moult cycle in *Portunus pelagicus* (Kuballa et al., 2011). Also, heart sarcoplasmic reticulum Ca^{2+}-ATPase (*SERCA*) mRNA expression declines in late premoult crayfish (Chen et al., 2002). This points to a lower degree of heart muscle remodelling than in skeletal muscle in premoult, and an inverse relationship, if any, between ecdysteroid and heart muscle growth (Qian et al., 2014). In intermoult, low levels of ecdysteroid may contribute to cardiac muscle growth via mTOR.

Phenotypic changes of the heart are mirrored in changes in mRNA expression of genes involved in muscle growth both during warm and cold acclimation in fish (e.g. Keen et al., 2016). Furthermore, cardiac transcriptomes vary after heat shock according to seasonal and latitudinal acclimatization in porcelain crabs (Stillman and Tagmount, 2009). In *M. magister* juveniles, cardiac expression patterns of mTOR components point to a general cold compensation of the mTOR signalling pathway, as expression of activating kinases (*Mm-AKT*, *Mm-mTOR* and *Mm-S6K*) and the inhibitory *Mm-AMPK* differ to the same extent (Fig. 6). The temperature effect was most pronounced in *Mm-Rheb* with the largest expression differences found in this study (Fig. 6A). That *Mm-Rheb* was not downregulated during warm exposure is clearly evident from overlapping 15 and 20°C regression lines when correlation to ecdysteroid concentration was tested (Fig. 7C). This indicates incomplete warm compensation of protein turnover as both protein synthesis and degradation may increase with temperature (Storch et al., 2003, 2005; Todgham et al., 2017; Whiteley et al., 1997). In agreement with this, cold acclimation of cardiac performance was observed in adult *M. magister* (Prentice and Schneider, 1979), whereas there was no evidence for seasonal (warm) acclimatization in juveniles (McLean and Todgham, 2015). Increased AMPK expression or activation may be a transient phenomenon during acute heat stress, helping to rapidly reduce energy consumption (Frederich et al., 2009; Jost et al., 2012; Han et al., 2013). Our data do not point to mTOR inhibition, and thus reduced growth, of the heart at 20°C. A sustained level of mTOR activation may aid to maintain cardiac muscle capacity (Sciarretta et al., 2014) at chronically increased heart rates expected owing to the lack of seasonal acclimatization (McLean and Todgham, 2015) at the cost of reduced body growth (Kondzela and Shirley, 1993; Terwilliger and Dumler, 2001). Body growth can only take place in the thermal range in which energy supply from aerobic metabolism exceeds maintenance costs (Pörtner and Knust, 2007; Pörtner, 2010; Sokolova et al., 2012). The thermal range that allows moulting and growth is relevant for the biogeography of a species. Knowledge of the underlying mechanisms of thermal tolerance can help to explain and predict past and future changes in distribution and biodiversity owing to climate change with impacts on fisheries (García Molinos et al., 2016; Green et al., 2014; Holsman et al., 2003; Moloney et al., 1994; Quinn, 2017; Toft et al., 2014).

Conclusions

Consistent with previous findings, Y-organ *Rheb* mRNA levels were positively correlated with ecdysteroid titres, which indicates that Rheb is central to regulating ecdysteroidogenesis through the mTOR pathway (Chang and Mykles, 2011; Das et al., 2018; Shyamal et al., 2018). Expression patterns of the GTPase *Mm-Rheb* may relate to temperature-dependent mTOR activation and protein synthesis during the moult cycle of juvenile *M. magister*. In all three organs, *Mm-Rheb* expression correlated most strongly with ecdysteroid titres at 20°C, which may indicate the tightest regulation of *Mm-Rheb* (and, vice versa, ecdysteroid production in Y-organs) compared with lower temperatures. This may point towards a need to control metabolic demand more stringently at higher temperatures.

Fig. 8 summarizes the effects of temperature on mRNA levels in the eyestalk ganglia, Y-organ and heart of juvenile *M. magister*. In intermoult, MIH inhibits mTOR signalling in the Y-organ, resulting in low ecdysteroid synthesis and secretion (Chang and Mykles, 2011). Low levels of ecdysteroid may foster growth of the heart. Temperature-dependent expression of mTOR signalling genes in the eyestalk ganglia and Y-organ and *Mm-MIH* in the eyestalk ganglia contributes to temperature compensation of moult control between 10 and 20°C. However, thermal compensation in the heart may be incomplete. The limited capacity for acclimation or acclimatization to 20°C in juvenile *M. magister* was apparent, as

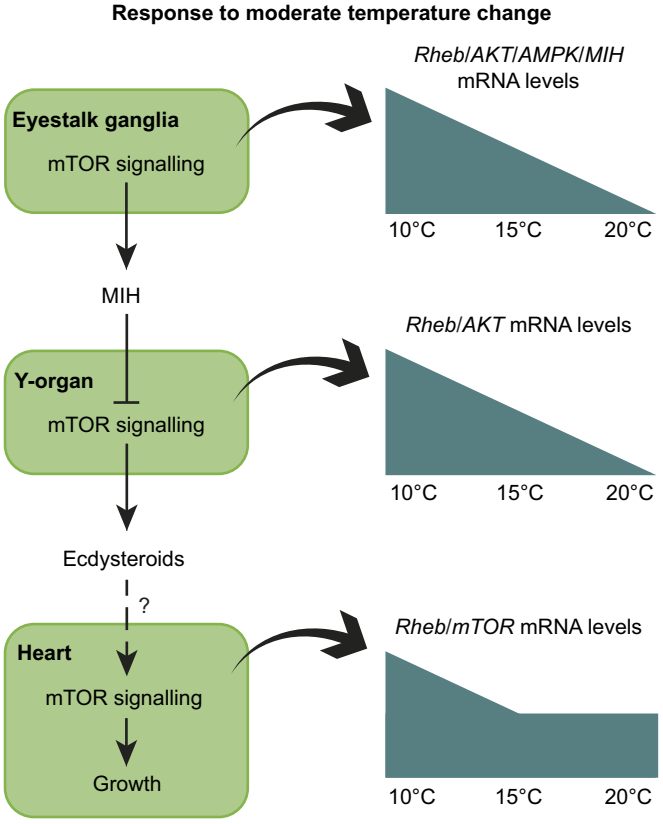

Fig. 8. Effects of moderate thermal stress on moulting and growth through the mTOR signalling pathway in juvenile crabs. In intermoult, MIH keeps the Y-organ in a basal or inhibited state with low ecdysteroid secretion by inhibiting mTOR. Low levels of ecdysteroid may stimulate heart muscle growth via mTOR signalling. Moderate temperature change (10 to 20°C range) allows acclimation of the animals, at least with respect to some physiological functions. After 14 days, thermal compensation is observed in moult control, i.e. similar ecdysteroid titre across temperatures throughout the moult cycle. Mechanisms include upregulation or downregulation of *Mm-MIH* and mTOR signalling genes (*Mm-Rheb*, *Mm-AKT*, *Mm-AMPK*) during cold (10°C) or warm (20°C) exposure in the eyestalk ganglia and Y-organ. In the heart, thermal compensation of metabolism is incomplete, as oxygen demand and heart activity increase with temperature. A sustained mRNA level of *Mm-Rheb* and *Mm-mTOR* indicates a greater allocation of energy to maintaining cardiac capacity during warm exposure.

indicated in the gene expression patterns in the heart after 14 days. Lack of downregulation of cardiac *Mm-Rheb* and other mTOR components at 20°C may relate to higher protein turnover and rising maintenance costs, which may result in similar moult stage progressions at 15 and 20°C. Insufficient warm compensation of heart function may contribute to the negative effects of high temperature on long-term growth and survival. This is consistent with previous studies of juvenile *M. magister*: successful moulting occurs up to about 20°C and reduced body growth occurs at temperatures above about 15°C (Kondzela and Shirley, 1993; Terwilliger and Dumler, 2001). Future studies should quantify phosphorylation of the protein kinases (e.g. mTOR, AMPK, AKT and S6K) to determine temperature-dependent activation or inhibition of mTOR signalling throughout the moult cycle. Furthermore, studying the mechanisms involved in the crosstalk between tissues will enable us to gain new insights into how moulting and growth are regulated in response to environmental stressors.

Acknowledgements
We thank A. Abuhagr, K. Cosenza, N. Pitts and M. (Mudron) Hines for technical advice on molecular techniques; J. He and H. Jesberger for cloning *Mm-mTOR* and *Mm-CHH*, respectively; K. Holle for analysing heart tissue; S. Chang for instruction and assistance on ecdysteroid ELISA; S. Nimitkul for advice on dissections; E. Grosholz for the use of pit traps; Bodega Marine Laboratory staff J. Newman and K. Menard for assistance with experimental setup; E. Ernst for assistance with animal care and experimental setup; and D. Storch for helpful comments on the manuscript.

Competing interests
The authors declare no competing or financial interests.

Author contributions
Conceptualization: A.C.W., D.L.M.; Methodology: A.C.W., D.L.M.; Validation: A.C.W.; Formal analysis: A.C.W.; Investigation: A.C.W., S.A.M.B., D.A.L.-C.; Resources: A.C.W., D.L.M, E.S.C.; Writing - original draft: A.C.W.; Writing - review & editing: A.C.W., S.A.M.B., D.A.L.-C., E.S.C., D.L.M.; Visualization: A.C.W.; Supervision: A.C.W., E.S.C., D.L.M.; Project administration: A.C.W., D.L.M.; Funding acquisition: A.C.W., E.S.C., D.L.M.

Funding
Funding was provided by a European Union Seventh Framework Programme People: Marie Sklodovska Curie International Outgoing Fellowship PIOF-GA-2012-326483 to A.C.W. and National Science Foundation grant IOS-1257732 to D.L.M. and E.S.C.

Data availability
New sequences identified in this study have been submitted to GenBank under the accession numbers KT285226, KT315720, KT315721, KT315722, KT315723, KT367806, KT367807 and KY070318 (https://www.ncbi.nlm.nih.gov/genbank/).

Supplementary information
Supplementary information available online at
http://jeb.biologists.org/lookup/doi/10.1242/jeb.187492.supplemental

References
Abuhagr, A. M., Blindert, J. L., Nimitkul, S., Zander, I. A., LaBere, S. M., Chang, S. A., MacLea, K. S., Chang, E. S. and Mykles, D. L. (2014a). Molt regulation in green and red color morphs of the crab *Carcinus maenas*: gene expression of molt-inhibiting hormone signaling components. *J. Exp. Biol.* **217**, 796-808.

Abuhagr, A. M., MacLea, K. S., Chang, E. S. and Mykles, D. L. (2014b). Mechanistic target of rapamycin (mTOR) signaling genes in decapod crustaceans: cloning and tissue expression of mTOR, Akt, Rheb, and p70 S6 kinase in the green crab, *Carcinus maenas*, and blackback land crab, *Gecarcinus lateralis*. *Comp. Biochem. Physiol., A: Mol. Integr. Physiol.* **168**, 25-39.

Abuhagr, A. M., MacLea, K. S., Mudron, M. R., Chang, S. A., Chang, E. S. and Mykles, D. L. (2016). Roles of mechanistic target of rapamycin and transforming growth factor-β signaling in the molting gland (Y-organ) of the blackback land crab, *Gecarcinus lateralis*. *Comp. Biochem. Physiol. A: Mol. Integr. Physiol.* **198**, 15-21.

Aiken, D. E. and Waddy, S. L. (1975). Temperature increase can cause hyperecdysonism in American lobsters (*Homarus americanus*) injected with ecdysterone. *J. Fish. Res. Board Can.* **32**, 1843-1845.

Aiken, D. E. and Waddy, S. L. (1976). Controlling growth and reproduction in the American lobster. *Proc. Annu. Meeting World Mariculture Soc.* **7**, 415-430.

Aiken, D. E. and Waddy, S. L. (1992). The growth process in crayfish. *Rev. Aquat. Sci.* **6**, 335-381.

Anger, K. (1987). The D_0 threshold: a critical point in the larval development of decapod crustaceans. *J. Exp. Mar. Biol. Ecol.* **108**, 15-30.

Anger, K. and Spindler, K.-D. (1987). Energetics, moult cycle and ecdysteroid titers in spider crab (*Hyas araneus*) larvae starved after the D_0 threshold. *Mar. Biol.* **94**, 367-375.

Anttila, K., Casselman, M. T., Schulte, P. M. and Farrell, A. P. (2013). Optimum temperature in juvenile salmonids: connecting subcellular indicators to tissue function and whole-organism thermal optimum. *Physiol. Biochem. Zool.* **86**, 245-256.

Aramburu, J., Ortells, M. C., Tejedor, S., Buxadé, M. and López-Rodríguez, C. (2014). Transcriptional regulation of the stress response by mTOR. *Sci. Signal.* **7**, re2.

Arquier, N., Delanoue, R. and Leopold, P. (2010). The systemic control of growth, physiology, and behaviour by TOR signaling in *Drosophila*. In *The Enzymes*, vol. 28 (ed. F. Tamanoi and M. N. Hall), pp. 289-204. London: Elsevier Academic Press.

Bandhakavi, S., Xie, H., O'Callaghan, B., Sakurai, H., Kim, D.-H. and Griffin, T. J. (2008). Hsf1 activation inhibits rapamycin resistance and TOR signaling in yeast revealed by combined proteomic and genetic analysis. *PloS One* **3**, e1598.

Bodine, S. C., Stitt, T. N., Gonzalez, M., Kline, W. O., Stover, G. L., Bauerlein, R., Zlotchenko, E., Scrimgeour, A., Lawrence, J. C., Glass, D. J. et al. (2001). Akt/mTOR pathway is a crucial regulator of skeletal muscle hypertrophy and can prevent muscle atrophy *in vivo*. *Nat. Cell Biol.* **3**, 1014-1019.

Brown, A. C., Terwilliger, N. B. (1999). Developmental changes in oxygen uptake in *Cancer magister* (Dana) in response to changes in salinity and temperature. *J. Exp. Mar. Biol. Ecol.* **241**, 179-192.

Brugman, A. J. (1972). The effects of temperature on the growth of the Dungeness crab, *Cancer magister* Dana, *MSc thesis*, Humboldt State University, Arcata, CA, USA.

Chang, E. S. and Bruce, M. J. (1980). Ecdysteroid titers of juvenile lobsters following molt induction. *J. Exp. Zool. A Ecol. Integr. Physiol.* **214**, 157-160.

Chang, E. S. and Mykles, D. L. (2011). Regulation of crustacean molting: a review and our perspectives. *Gen. Comp. Endocrinol.* **172**, 323-330.

Charmantier-Daures, M. and Vernet, G. (2004). Moulting, autotomy, and regeneration. In *The Crustacea*, vol. 1 (ed. J. Forest, J. C. von Vaupel Klein and F. R. Schram), pp. 161-255. Leiden: Brill.

Chen, D., Zhang, Z., Wheatly, M. G. and Gao, Y. (2002). Cloning and characterization of the heart muscle isoform of sarco/endoplasmic reticulum Ca^{2+} ATPase (SERCA) from crayfish. *J. Exp. Biol.* **205**, 2677-2686.

Chou, S.-D., Prince, T., Gong, J. and Calderwood, S. K. (2012). mTOR is essential for the proteotoxic stress response, HSF1 activation and heat shock protein synthesis. *PloS One* **7**, e39679.

Chung, J. S. and Webster, S. G. (2003). Moult cycle-related changes in biological activity of moult-inhibiting hormone (MIH) and crustacean hyperglycaemic hormone (CHH) in the crab, *Carcinus maenas*. *Eur. J. Biochem.* **270**, 3280-3288.

Chung, J. S. and Webster, S. G. (2005). Dynamics of *in vivo* release of molt-inhibiting hormone and crustacean hyperglycemic hormone in the shore crab, *Carcinus maenas*. *Endocrinology* **146**, 5545-5551.

Clark, M. S., Thorne, M. A. S., Amaral, A., Vieira, F., Batista, F. M., Reis, J. and Power, D. M. (2013). Identification of molecular and physiological responses to chronic environmental challenge in an invasive species: the Pacific oyster, *Crassostrea gigas*. *Ecol. Evol.* **3**, 3283-3297.

Cosenza, K. S. (2016). The role of ecdysteroids on myostatin and mTOR signaling gene expression in molt-dependent growth and atrophy of skeletal muscle in *Gecarcinus lateralis* and *Carcinus maenas*. *PhD thesis*, Colorado State University, Fort Collins, CO, USA.

Covi, J. A., Bader, B. D., Chang, E. S. and Mykles, D. L. (2010). Molt cycle regulation of protein synthesis in skeletal muscle of the blackback land crab, *Gecarcinus lateralis*, and the differential expression of a myostatin-like factor during atrophy induced by molting or unweighting. *J. Exp. Biol.* **213**, 172-183.

Covi, J. A., Chang, E. S. and Mykles, D. L. (2012). Neuropeptide signaling mechanisms in crustacean and insect molting glands. *Invertebr. Reprod. Dev.* **56**, 33-49.

Danielsen, E. T., Moeller, M. E., Yamanaka, N., Ou, Q., Laursen, J. M., Soenderholm, C., Zhuo, R., Phelps, B., Tang, K., Zeng, J. et al. (2016). A *Drosophila* genome-wide screen identifies regulators of steroid hormone production and developmental timing. *Dev. Cell* **37**, 558-570.

Das, S., Pitts, N. L., Mudron, M. R., Durica, D. S. and Mykles, D. L. (2016). Transcriptome analysis of the molting gland (Y-organ) from the blackback land crab, *Gecarcinus lateralis*. *Comp. Biochem. Physiol. D* **17**, 26-40.

Das, S., Vraspir, L., Zhou, W., Durica, D. S. and Mykles, D. L. (2018). Transcriptomic analysis of differentially expressed genes in the molting gland

(Y-organ) of the blackback land crab, *Gecarcinus lateralis*, during molt-cycle stage transitions. *Comp. Biochem. Physiol. D* **28**, 37-53.
de Oliveira Cesar, J. R., Zhao, B., Malecha, S., Ako, H. and Yang, J. (2006). Morphological and biochemical changes in the muscle of the marine shrimp *Litopenaeus vannamei* during the molt cycle. *Aquaculture* **261**, 688-694.
Drach, P. and Tchernigovtzeff, C. (1967). Sur la méthode de determination des stades d'intermue et son application générale aux crustacés. *Vie Milieu* **18**, 595-607.
El Haj, A., Clarke, S., Harrison, P. and Chang, E. (1996). *In vivo* muscle protein synthesis rates in the American lobster *Homarus americanus* during the moult cycle and in response to 20-hydroxyecdysone. *J. Exp. Biol.* **199**, 579-585.
Frederich, M., O'Rourke, M. R., Furey, N. B. and Jost, J. A. (2009). AMP-activated protein kinase (AMPK) in the rock crab, *Cancer irroratus*: an early indicator of temperature stress. *J. Exp. Biol.* **212**, 722-730.
García Molinos, J., Halpern, B. S., Schoeman, D. S., Brown, C. J., Kiessling, W., Moore, P. J., Pandolfi, J. M., Poloczanska, E. S., Richardson, A. J. and Burrows, M. T. (2016). Climate velocity and the future global redistribution of marine biodiversity. *Nat. Clim. Change* **6**, 83-88.
Gibney, P. A., Lu, C., Caudy, A. A., Hess, D. C. and Botstein, D. (2013). Yeast metabolic and signaling genes are required for heat-shock survival and have little overlap with the heat-induced genes. *Proc. Natl. Acad. Sci. USA* **110**, E4393-E4402.
Goodman, C. A., Frey, J. W., Mabrey, D. M., Jacobs, B. L., Lincoln, H. C., You, J.-S. and Hornberger, T. A. (2011). The role of skeletal muscle mTOR in the regulation of mechanical load-induced growth. *J. Physiol. (Lond.)* **589**, 5485-5501.
Green, B. S., Gardner, C., Hochmuth, J. D. and Linnane, A. (2014). Environmental effects on fished lobsters and crabs. *Rev. Fish Biol. Fish.* **24**, 613-638.
Grosholz, E. D. and Ruiz, G. M. (1995). Spread and potential impact of the recently introduced European green crab, *Carcinus maenas*, in central California. *Mar. Biol.* **122**, 239-247.
Gutermuth, F. B. and Armstrong, D. A. (1989). Temperature-dependent metabolic response of juvenile Dungeness crab *Cancer magister* Dana: ecological implications for estuarine and coastal populations. *J. Exp. Mar. Biol. Ecol.* **126**, 135-144.
Hall, D. J., Grewal, S. S., de la Cruz, A. F. A. and Edgar, B. A. (2007). Rheb-TOR signaling promotes protein synthesis, but not glucose or amino acid import, in *Drosophila*. *BMC Biol.* **5**, 10.
Han, G.-D., Zhang, S., Marshall, D. J., Ke, C.-H. and Dong, Y.-W. (2013). Metabolic energy sensors (AMPK and SIRT1), protein carbonylation and cardiac failure as biomarkers of thermal stress in an intertidal limpet: linking energetic allocation with environmental temperature during aerial emersion. *J. Exp. Biol.* **216**, 3273-3282.
Hansen, M., Taubert, S., Crawford, D., Libina, N., Lee, S.-J. and Kenyon, C. (2007). Lifespan extension by conditions that inhibit translation in *Caenorhabditis elegans*. *Aging Cell* **6**, 95-110.
Hardie, D. G., Hawley, S. A. and Scott, J. W. (2006). AMP-activated protein kinase - Development of the energy sensor concept. *J. Physiol. (Lond.)* **574**, 7-15.
Holsman, K. K., Armstrong, D. A., Beauchamp, D. A. and Ruesink, J. L. (2003). The necessity for intertidal foraging by estuarine populations of subadult Dungeness crab, *Cancer magister*: evidence from a bioenergetics model. *Estuaries* **26**, 1155-1173.
Huang, H., Fu, C., Chen, X., Gong, J., Huang, X. and Ye, H. (2015). Molt-inhibiting hormone (MIH) gene from the green mud crab *Scylla paramamosain* and its expression during the molting and ovarian cycle. *Aquacult. Res.* **46**, 2665-2675.
Jarolim, S., Ayer, A., Pillay, B., Gee, A. C., Phrakaysone, A., Perrone, G. G., Breitenbach, M. and Dawes, I. W. (2013). *Saccharomyces cerevisiae* genes involved in survival of heat shock. *G3-Genes Genom. Genet.* **3**, 2321-2333.
Johnson, C. L. (2003). Ecdysteroids in the oceanic copepod *Calanus pacificus*: variation during the molt cycle and change associated with diapause. *Mar. Ecol. Prog. Ser.* **257**, 159-165.
Jost, J. A., Podolski, S. M. and Frederich, M. (2012). Enhancing thermal tolerance by eliminating the pejus range: a comparative study with three decapod crustaceans. *Mar. Ecol. Prog. Ser.* **444**, 263-274.
Keen, A. N., Fenna, A. J., McConnell, J. C., Sherratt, M. J., Gardner, P. and Shiels, H. A. (2016). The dynamic nature of hypertrophic and fibrotic remodeling of the fish ventricle. *Front. Physiol.* **6**, 427.
Kingan, T. G. (1989). A competitive enzyme-linked immunosorbent assay: applications in the assay of peptides, steroids, and cyclic nucleotides. *Anal. Biochem.* **183**, 283-289.
Kondzela, C. M. and Shirley, T. C. (1993). Survival, feeding, and growth of juvenile Dungeness crabs from Southeastern Alaska reared at different temperatures. *J. Crust. Biol.* **13**, 25-35.
Kuballa, A. V., Holton, T. A., Paterson, B. and Elizur, A. (2011). Moult cycle specific differential gene expression profiling of the crab *Portunus pelagicus*. *BMC Genomics* **12**, 147.
Layalle, S., Arquier, N. and Léopold, P. (2008). The TOR pathway couples nutrition and developmental timing in *Drosophila*. *Dev. Cell* **15**, 568-577.
Lee, K. J., Watson, R. D. and Roer, R. D. (1998). Molt-inhibiting hormone mRNA levels and ecdysteroid titer during a molt cycle of the Blue crab, *Callinectes sapidus*. *Biochem. Biophys. Res. Commun.* **249**, 624-627.
Long, X., Lin, Y., Ortiz-Vega, S., Yonezawa, K. and Avruch, J. (2005). Rheb binds and regulates the mTOR kinase. *Curr. Biol.* **15**, 702-713.
MacLea, K. S., Abuhagr, A. M., Pitts, N. L., Covi, J. A., Bader, B. D., Chang, E. S. and Mykles, D. L. (2012). *Rheb*, an activator of target of rapamycin, in the blackback land crab, *Gecarcinus lateralis*: cloning and effects of molting and unweighting on expression in skeletal muscle. *J. Exp. Biol.* **215**, 590-604.
Martin, M., Fehsenfeld, S., Sourial, M. M. and Weihrauch, D. (2011). Effects of high environmental ammonia on branchial ammonia excretion rates and tissue Rh-protein mRNA expression levels in seawater acclimated Dungeness crab *Metacarcinus magister*. *Comp. Biochem. Physiol., A: Mol. Integr. Physiol.* **160**, 267-277.
McLean, K. M. and Todgham, A. E. (2015). Effect of food availability on the growth and thermal physiology of juvenile Dungeness crabs (*Metacarcinus magister*). *Conserv. Physiol.* **3**, cov013.
Moloney, C. L., Botsford, L. W. and Largier, J. L. (1994). Development, survival and timing of metamorphosis of planktonic larvae in a variable environment: the Dungeness crab as an example. *Mar. Ecol. Prog. Ser.* **133**, 61-79.
Moriyasu, M. and Mallet, P. (1986). Molt stages of the snow crab *Chionoecetes opilio* by observation of morphogenesis of setae on the maxilla. *J. Crust. Biol.* **6**, 709-718.
Mykles, D. L. (2011). Ecdysteroid metabolism in crustaceans. *J. Steroid Biochem. Mol. Biol.* **127**, 196-203.
Mykles, D. L. and Medler, S. (2015). Skeletal muscle differentiation, growth, and plasticity. In *Physiology*, vol. 4 (ed. E. S. Chang and M. Thiel), pp. 134-167. Oxford: Oxford University Press.
Nijhout, H. F., Riddiford, L. M., Mirth, C., Shingleton, A. W., Suzuki, Y. and Callier, V. (2014). The developmental control of size in insects. *WIREs Dev. Biol.* **3**, 113-134.
Parthasarathy, R. and Palli, S. R. (2011). Molecular analysis of nutritional and hormonal regulation of female reproduction in the red flour beetle, *Tribolium castaneum*. *Insect Biochem. Mol. Biol.* **41**, 294-305.
Pitts, N. L. and Mykles, D. L. (2017). Localization and expression of molt-inhibiting hormone and nitric oxide synthase in the central nervous system of the green shore crab, *Carcinus maenas*, and the blackback land crab, *Gecarcinus lateralis*. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* **203**, 328-340.
Pitts, N. L., Schulz, H. M., Oatman, S. R. and Mykles, D. L. (2017). Elevated expression of neuropeptide signaling genes in the eyestalk ganglia and Y-organ of *Gecarcinus lateralis* individuals that are refractory to molt induction. *Comp. Biochem. Physiol, A Mol. Integr. Physiol.* **214**, 66-78.
Pörtner, H.-O. (2010). Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ectotherms. *J. Exp. Biol.* **213**, 881-893.
Pörtner, H. O. and Knust, R. (2007). Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* **315**, 95-97.
Prentice, E. F. and Schneider, D. E. (1979). Respiration and thermal tolerance of the Dungeness crab, *Cancer magister* Dana. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* **63**, 591-597.
Qian, Z., He, S., Liu, T., Liu, Y., Hou, F., Liu, Q., Wang, X., Mi, X., Wang, P. and Liu, X. (2014). Identification of ecdysteroid signaling late-response genes from different tissues of the Pacific white shrimp, *Litopenaeus vannamei*. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* **172**, 10-30.
Quinn, B. K. (2017). Threshold temperatures for performance and survival of American lobster larvae: a review of current knowledge and implications to modeling impacts of climate change. *Fish. Res.* **186**, 383-396.
Reiling, J. H. and Sabatini, D. M. (2006). Stress and mTORture signaling. *Oncogene* **25**, 6373-6383.
Saxton, R. A. and Sabatini, D. M. (2017). mTOR signaling in growth, metabolism, and disease. *Cell* **168**, 960-976.
Sciarretta, S., Volpe, M. and Sadoshima, J. (2014). Mammalian target of Rapamycin signaling in cardiac physiology and disease. *Circul. Res.* **114**, 549-564.
Sengupta, S., Peterson, T. R., Laplante, M., Oh, S. and Sabatini, D. M. (2010). mTORC1 controls fasting-induced ketogenesis and its modulation by ageing. *Nature* **468**, 1100.
Shyamal, S., Das, S., Guruacharya, A., Mykles, D. L. and Durica, D. S. (2018). Transcriptomic analysis of crustacean molting gland (Y-organ) regulation via the mTOR signaling pathway. *Sci. Rep.* **8**, 7307.
Skinner, D. M. (1985). Molting and regeneration. In *The Biology of Crustacea, Vol. 9: Integument, Pigments, and Hormonal Processes* (ed. D. E. Bliss and L. H. Mantel), pp. 43-146. Orlando: Academic Press.
Sokolova, I. M., Frederich, M., Bagwe, R., Lannig, G. and Sukhotin, A. A. (2012). Energy homeostasis as an integrative tool for assessing limits of environmental stress tolerance in aquatic invertebrates. *Mar. Environ. Res.* **79**, 1-15.
Stillman, J. H. and Tagmount, A. (2009). Seasonal and latitudinal acclimatization of cardiac transcriptome responses to thermal stress in porcelain crabs, *Petrolisthes cinctipes*. *Mol. Ecol.* **18**, 4206-4226.

Storch, D., Heilmayer, O., Hardewig, I. and Pörtner, H. O. (2003). *In vitro* protein synthesis capacities in a cold stenothermal and a temperate eurythermal pectinid. *J. Comp. Physiol., B* **173**, 611-620.
Storch, D., Lannig, G. and Pörtner, H. O. (2005). Temperature-dependent protein synthesis capacities in Antarctic and temperate (North Sea) fish (Zoarcidae). *J. Exp. Biol.* **208**, 2409-2420.
Sulkin, S. D. and McKeen, G. L. (1989). Laboratory study of survival and duration of individual zoeal stages as a function of temperature in the brachyuran crab *Cancer magister*. *Mar. Biol.* **103**, 31-37.
Sulkin, S. D., Mojica, E. and McKeen, G. L. (1996). Elevated summer temperature effects on megalopal and early juvenile development in the Dungeness crab, *Cancer magister*. *Can. J. Fish. Aquat. Sci.* **53**, 2076-2079.
Tamone, S. L., Taggart, S. J., Andrews, A. G., Mondragon, J. and Nielsen, J. K. (2007). The relationship between circulating ecdysteroids and chela allometry in male Tanner crabs: evidence for a terminal molt in the genus *Chionoecetes*. *J. Crust. Biol.* **27**, 635-642.
Tasto, R. N. (1983). Juvenile Dungeness crab, *Cancer magister*, studies in the San Francisco Bay area. In *Life History, Environment, and Mariculture Studies of the Dungeness crab, Cancer magister, with Emphasis on the Central California Fishery Resource*. Fish Bulletin 172 (ed. P. W. Wild and R. N. Tasto), pp. 135-154. Sacramento: California Department of Fish and Game.
Techa, S. and Chung, J. S. (2015). Ecdysteroids regulate the levels of molt-inhibiting hormone (*MIH*) expression in the Blue crab, *Callinectes sapidus*. *PloS One* **10**, e0117278.
Techa, S., Alvarez, J. V. and Sook Chung, J. (2015). Changes in ecdysteroid levels and expression patterns of ecdysteroid-responsive factors and neuropeptide hormones during the embryogenesis of the blue crab, *Callinectes sapidus*. *Gen. Comp. Endocrinol.* **214**, 157-166.
Tepolt, C. K. and Somero, G. N. (2014). Master of all trades: thermal acclimation and adaptation of cardiac function in a broadly distributed marine invasive species, the European green crab, *Carcinus maenas*. *J. Exp. Biol.* **217**, 1129-1138.
Terwilliger, N. B. and Dumler, K. (2001). Ontogeny of decapod crustacean hemocyanin: effects of temperature and nutrition. *J. Exp. Biol.* **204**, 1013-1020.
Thomton, J. D., Tamone, S. L. and Atkinson, S. (2006). Circulating ecdysteroid concentrations in Alaskan Dungeness crab (*Cancer magister*). *J. Crust. Biol.* **26**, 176-181.
Todgham, A. E., Crombie, T. A. and Hofmann, G. E. (2017). The effect of temperature adaptation on the ubiquitin–proteasome pathway in notothenioid fishes. *J. Exp. Biol.* **220**, 369-378.
Toft, J. E., Burke, J. L., Carey, M. P., Kim, C. K., Marsik, M., Sutherland, D. A., Arkema, K. K., Guerry, A. D., Levin, P. S., Minello, T. J. et al. (2014). From mountains to sound: modelling the sensitivity of Dungeness crab and Pacific oyster to land–sea interactions in Hood Canal, WA. *ICES J. Mar. Sci.* **71**, 725-738.
Umphrey, H. R., Lee, K. J., Watson, R. D. and Spaziani, E. (1998). Molecular cloning of a cDNA encoding molt-inhibiting hormone of the crab, *Cancer magister*. *Mol. Cell. Endocrinol.* **136**, 145-149.
Webster, S. G. (2015). Endocrinology of molting. In *Physiology*, vol. 4 (ed. E. S. Chang and M. Thiel), pp. 1-35. Oxford: Oxford University Press.
Webster, S. G., Keller, R. and Dircksen, H. (2012). The CHH-superfamily of multifunctional peptide hormones controlling crustacean metabolism, osmoregulation, moulting, and reproduction. *Gen. Comp. Endocrinol.* **175**, 217-233.
Whiteley, N. M., Taylor, E. W. and El Haj, A. J. (1997). Seasonal and latitudinal adaptation to temperature in crustaceans. *J. Therm. Biol.* **22**, 419-427.
Windisch, H. S., Kathöver, R., Pörtner, H.-O., Frickenhaus, S. and Lucassen, M. (2011). Thermal acclimation in Antarctic fish: transcriptomic profiling of metabolic pathways. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **301**, R1453-R1466.
Windisch, H. S., Frickenhaus, S., John, U., Knust, R., Pörtner, H.-O. and Lucassen, M. (2014). Stress response or beneficial temperature acclimation: transcriptomic signatures in Antarctic fish (*Pachycara brachycephalum*). *Mol. Ecol.* **23**, 3469-3482.
Wittmann, A. C., Pörtner, H. O. and Sartoris, F. J. (2012). A role for oxygen delivery and extracellular magnesium in limiting cold tolerance of the sub-Antarctic stone crab *Paralomis granulosa*? *Physiol. Biochem. Zool.* **85**, 285-298.