

**Elevated cortisol lowers thermal tolerance but results in limited cardiac remodelling in rainbow trout (*Oncorhynchus mykiss*) experiencing chronic social stress**

Brittany Bard<sup>1</sup>, Annette Dodge<sup>1</sup>, William Joyce<sup>1,2</sup>, Michael Lawrence<sup>3</sup>, Steven J Cooke<sup>3</sup>, and Kathleen M Gilmour<sup>1\*</sup>

<sup>1</sup>Department of Biology, University of Ottawa, Ottawa, ON, Canada

<sup>2</sup>Department of Biology – Zoophysiology, Aarhus University, Aarhus C, Denmark

<sup>3</sup>Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, ON, Canada

\*Correspondence to:  
Dr. K.M. Gilmour  
Department of Biology  
University of Ottawa  
30 Marie Curie  
Ottawa, ON  
K1N 6T2  
Canada  
Phone 613-562-5800 x6004  
e-mail kgilmour@uottawa.ca

**Abstract**

Juvenile rainbow trout (*Oncorhynchus mykiss*) held in pairs form dominance hierarchies in which subordinate individuals experience chronic social stress accompanied by lowered thermal tolerance (assessed as the critical thermal maximum, CT<sub>max</sub>). Here we tested the hypothesis that chronic elevation of circulating cortisol levels reduces thermal tolerance in subordinate trout. In

support of this hypothesis, subordinate trout that recovered from social stress for 48 h, a period sufficient to return cortisol to normal baseline levels, no longer showed reduced CT<sub>max</sub>. Further, thermal tolerance was not restored in subordinates treated with cortisol during recovery from social stress. To explore possible mechanisms underlying the effect of chronic stress on CT<sub>max</sub>, we also tested the hypothesis that chronic cortisol elevation induces cardiac remodelling in subordinate trout, as previously reported for cortisol-treated rainbow trout. Ventricle mass and cardiac hypertrophy markers were unaffected by social stress. Picrosirius red staining revealed a trend for lower collagen levels in the ventricles of subordinate relative to dominant trout. However, collagen type I transcript and protein levels, and markers of collagen turnover were unaffected. Indicators of cardiac function, including ventricle passive stiffness and intrinsic heart rate ( $f_H$ ), similarly were unaffected. *In vivo*  $f_H$  was also similar between subordinate and dominant fish. Nevertheless, in keeping with their lower CT<sub>max</sub>, subordinate fish exhibited cardiac arrhythmia at significantly lower temperatures than dominant fish during CT<sub>max</sub> trials. Thus, high baseline cortisol levels in subordinate trout result in lowered thermal tolerance, but 5 d of social stress did not greatly affect cardiac structure and function.

**Key words:** CT<sub>max</sub>, cortisol, cardiac remodelling, heart rate

## Introduction

Juvenile rainbow trout (*Oncorhynchus mykiss*) held in pairs or small groups form social hierarchies through agonistic interactions. The resulting dominant and subordinate individuals differ not only in their behaviour, with dominant fish patrolling the water column, monopolizing food, and exhibiting aggression, but also physiologically. Most importantly, subordinate fish

experience chronic social stress as demonstrated by the prolonged elevation of circulating levels of the glucocorticoid stress hormone cortisol (Ejike and Schreck, 1980; Øverli et al., 1999a; Pottinger and Pickering, 1992; Sloman et al., 2001; Culbert and Gilmour, 2016, see reviews by Gilmour et al., 2005; Johnsson et al., 2005; Sørensen et al., 2013; Winberg et al., 2016). The use of these social hierarchies as a model to study the consequences of chronic stress has enabled the mechanisms underlying effects such as reduced growth and changes in intermediary metabolism to be probed, with elevated cortisol in combination with limited food intake emerging as causative factors (DiBattista et al., 2006; Gilmour et al., 2012; Kostyniuk et al., 2018). Subordinate trout also exhibit reduced tolerance of environmental challenges such as hypoxia (Thomas & Gilmour, 2012) and elevated temperature (LeBlanc et al., 2011), yet the mechanisms underlying these effects remain to be determined. The goal of the present study was to investigate whether and how chronic cortisol elevation contributes to the reduced thermal tolerance of subordinate rainbow trout.

A widely-used measure of acute thermal tolerance is the critical thermal maximum (CT<sub>max</sub>), the temperature at which an animal loses the ability to maintain physical equilibrium (Becker & Genoway, 1979; Lutterschmidt & Hutchison, 1997; Beitinger et al., 2000). Although CT<sub>max</sub> has been measured in many different fishes, the underlying physiology that results in the loss of equilibrium (LOE) during acute warming remains unclear and indeed, the physiological factors that determine thermal tolerance remain heavily debated (Fangue et al., 2011; Norin et al., 2014; Lefevre et al., 2016; Motyka et al., 2017; Pörtner et al., 2017; Jeffries et al., 2018; Jutfelt et al., 2018). The oxygen- and capacity-limited thermal tolerance (OCLTT) hypothesis suggests that thermal tolerance is limited by the capacity of the cardiorespiratory system to meet tissue oxygen demands (Pörtner, 2010). Empirical support for the OCLTT hypothesis has been

mixed, with evidence both for (e.g. Beers & Sidell, 2011; Devor et al., 2016; Muñoz et al., 2018; Blasco et al., 2020) and against (e.g. Wang et al., 2014; Ern et al., 2016; Ern et al., 2017; Jutfelt et al., 2019; Joyce and Perry, 2020) limitations in tissue oxygen supply as the cause of LOE at CTmax. In accordance with the OCLTT hypothesis, impaired cardiac function translates into lowering of CTmax (Ekström et al., 2017, 2019; Gilbert et al., 2019). Acute warming increases cardiac output in fishes, a response that is driven largely by increases in heart rate ( $f_H$ ) because stroke volume is maintained or increases relatively little during acute warming (e.g. Gollock et al., 2006; Steinhausen et al., 2008; Mendonça & Gamperl, 2010; Ekström et al., 2017, 2019; Joyce & Wang, 2020). As water temperature approaches CTmax, a plateau and/or decrease in  $f_H$  typically is observed (Gollock et al., 2006; Mendonça & Gamperl, 2010; Ekström et al., 2016, 2019; Joyce et al., 2018). In rainbow trout in which the coronary arteries of the heart were ligated, resting  $f_H$  was elevated,  $f_H$  peaked at a lower temperature than in control animals during acute warming, and CTmax was reduced (Ekström et al., 2019). Thus, factors that elevate resting  $f_H$  and/or limit maximum cardiac output may constrain cardiac performance during acute warming and hence CTmax.

Thomas and Gilmour (2012) reported significantly higher resting  $f_H$  in subordinate relative to dominant trout. In addition, Johansen et al. (2017) reported that chronic cortisol treatment increased resting  $f_H$  and lowered maximum cardiac output in rainbow trout, effects that were attributed to pathological ventricular hypertrophy. Specifically, dietary cortisol administration for 45 d elevated circulating cortisol concentrations to  $\sim 20 \text{ ng ml}^{-1}$ , increasing ventricular mass as well as transcript abundances of specific molecular markers associated with cardiac remodelling in mammals (Johansen et al., 2017). Ventricular hypertrophy also was detected in a line of rainbow trout selected for a high cortisol response to a standardized stressor ('high

responsiveness' (HR) trout; Pottinger and Carrick, 1999), in which it was accompanied by increased collagen deposition consistent with fibrosis (Johansen et al., 2011). Ventricular hypertrophy and fibrosis in this case were thought to be associated with the high cortisol levels routinely experienced by these fish during a stress response. Subordinate trout exhibit substantially higher cortisol levels than those used by Johansen et al. (2017), although for a relatively brief duration (few days). However, even 7 d of cortisol treatment were sufficient to induce molecular markers of ventricular hypertrophy (Nørstrud et al., 2018), suggesting a potential for cardiac remodelling in response to chronic social stress.

The present study aimed to identify the physiological mechanisms contributing to lower CTmax in subordinate rainbow trout. To test the hypothesis that elevated cortisol in subordinate fish lowers CTmax, we measured CTmax in subordinates recovering from social stress, where cortisol returns to normal baseline values, and in recovering subordinates treated with cortisol to prevent this fall in circulating cortisol levels. We predicted that the reestablishment of normal baseline cortisol levels during recovery from social stress would lead to recovery of CTmax, and that this recovery would be prevented if high cortisol levels were maintained. To investigate potential mechanisms linking CTmax to cortisol levels,  $f_H$  responses to social interactions and acute warming were measured together with markers of ventricular hypertrophy and fibrosis.

## **Materials and Methods**

### *Experimental animals*

Juvenile rainbow trout, *Oncorhynchus mykiss* (mass =  $109.4 \pm 2.2$  g, fork length =  $21.3 \pm 0.2$  cm, mean  $\pm$  SEM,  $N = 165$ ; see Table 1), were purchased from Linwood Acres Trout Farm (Campbellcroft, Ontario). Fish were held at the University of Ottawa in 1275 L fibreglass tanks

supplied with flowing, aerated, dechloraminated city of Ottawa tap water at a temperature of 13°C. A 12L:12D photoperiod was maintained, and fish were fed a ration of 0.5% body mass daily by scattering commercial trout pellets on the water's surface. Trout were acclimated to these holding conditions, which served to minimize hierarchy formation (e.g. use of scatter feeding, homogenous tanks with a mild current; Jeffrey et al., 2014; Kostyniuk et al., 2018), for at least 2 weeks prior to experimentation. All experimental protocols were approved by an institutional animal care committee (protocol BL-2118) and were in compliance with the guidelines of the Canadian Council on Animal Care (CCAC) for the use of animals in research and teaching.

Rainbow trout were allocated to pairs based on similar fork length (mean length difference =  $0.3 \pm 0.03$  cm,  $N = 80$  pairs) and mass (mean mass difference =  $5.0 \pm 0.4$  g,  $N = 80$  pairs) according to established protocols (LeBlanc et al., 2011; Jeffrey et al., 2014; Culbert & Gilmour, 2016). Fish were lightly anaesthetized (to the point of losing equilibrium) in a solution of benzocaine ( $0.05 \text{ g L}^{-1}$  ethyl-p-aminobenzoate; Sigma-Aldrich, Oakville, ON, CA) for the measurement of fork length and mass, and fin damage was assessed as per Moutou et al. (1998). The members of a pair were placed in 40 L flow-through Plexiglas 'behaviour' tanks separated by an opaque, perforated divider for an overnight recovery period. Tanks were supplied with flowing, aerated, dechloraminated city of Ottawa tap water at 13°C. The following morning, the divider was removed and the fish in a pair were allowed to interact for 4 d. Behaviour observations were carried out twice daily (morning and afternoon). Tank covers were adjusted to allow the fish to be observed. Following 10 min recovery from this minor disturbance, position in the tank, acts of aggression such as charges, chases and nips, and willingness to take a single pellet of food were recorded for 5 min. Points were awarded for each behaviour, with higher

scores for more dominant behaviours (Øverli et al., 1999a; Sloman et al., 2000; LeBlanc et al., 2011; Culbert & Gilmour, 2016). At the end of the 4-d interaction period, mean scores for individual behaviours over the interaction period were combined using a principal components analysis, and the fish within a pair with the higher behaviour score was assigned dominant social status. Pairs in which behaviour scores did not diverge by at least 0.5 were excluded from further analysis (a total of 10 pairs) (Jeffrey et al., 2014; Culbert & Gilmour, 2016). Shelters were added to the tank after the first observation period to provide a refuge and tanks were covered between observation periods to avoid disturbance of the fish. Fish were fed daily (after the afternoon observation period) from the second day of observations with a ration of 0.5% body mass.

Prior to the establishment of social hierarchies, a subset of trout ( $N = 10$  pairs plus  $N = 6$  shams; see Table 1) was fitted with commercially-available heart rate biologgers (DST micro-HRT, 8.3 mm  $\times$  25.4 mm, 3.3 g or  $2.35 \pm 0.05\%$  body mass, Star-Oddi, Iceland; <http://www.star-oddi.com/>) that were programmed to record temperature, heart rate ( $f_H$ ) and electrocardiogram (ECG) traces. Fish were anaesthetized by immersion in a solution of benzocaine as above, and after measuring weight, fork-length, and fin damage, fish were transferred to a surgical table that allowed continuous irrigation of the gills with the aerated anaesthetic solution. A 2 cm incision was made midline on the ventral surface just posterior to the pectoral girdle. Following Prystay et al. (2017), heart rate loggers were inserted into the peritoneal cavity through the incision to rest against the pericardial membrane, and sutured to the body wall with two stitches (2-0 surgical silk; Fisher Scientific, Nepean, ON, CA). The incision was closed using two single interrupted sutures. Fish were then transferred to the behaviour tanks as described above for a 20-h recovery period. Fish in the sham treatment group were prepared in the same way as fish

that were paired, but were placed individually in the behaviour tank (with the divider in place) to serve as a control for effects of handling associated with the establishment of social hierarchies.

### *Experimental protocols*

Three experiments were carried out. Experiment 1 investigated the effects of chronic social stress and elevated cortisol levels on CT<sub>max</sub>. Experiment 2 aimed to provide more information on differential responses of dominant versus subordinate fish to acute warming by investigating heart rate ( $f_H$ ) during a CT<sub>max</sub> trial. Experiment 3 investigated whether chronic social stress causes cardiac remodelling in subordinate trout.

### Experiment 1

Pairs of trout established as described above were allocated to one of eight treatment groups (Fig. S1). In group A ( $N = 6$  pairs), fish were subjected to a CT<sub>max</sub> trial (see below) at ~9 am on day 5. A non-lethal blood sample was collected 1 h after the return of water temperature to the acclimation temperature (13°C), and fish were euthanized on day 6 for the collection of heart tissue (see below). Blood was sampled 1 h after the thermal stress to assess the cortisol response to acute warming, and heart tissue was collected 24 h after thermal stress to assess the heat shock protein 70 (HSP70) response to acute warming; these sampling times were selected on the basis of a previous study that reported elevated cortisol concentrations and HSP70 protein abundances to a heat shock protocol of comparable length to the current CT<sub>max</sub> trial (LeBlanc et al. 2011). The fish of group B ( $N = 8$  pairs) followed the same protocol as group A but were not subjected to a CT<sub>max</sub> trial. Thus, samples collected from these fish reflected the effects of social interactions alone, whereas those collected from the fish of group A reflected the effects of

thermal stress on top of social interactions. In group C ( $N = 6$  pairs), the members of a pair were separated after the 4-d interaction period by re-insertion of the opaque divider, and were allowed to recover from social interactions for 2 d, following which they were subjected to a CTmax trial on day 7, with subsequent blood sample collection as for group A. The 2-d recovery period was chosen based on the findings of Culbert & Gilmour (2016) that circulating cortisol levels in subordinate fish had returned to normal baseline values within 2 d of physical separation from their dominant tank-mate. The protocol for group D ( $N = 7$  pairs) matched that of group C but lacked the CTmax trial. In groups E ( $N = 6$  pairs) and F ( $N = 6$  pairs), the protocols used for groups C and D were followed, except that subordinates were given cortisol suspended in cocoa butter implants (see below) immediately prior to the 2 d recovery period. The implant served to maintain elevated cortisol concentrations in subordinate fish during the recovery period. Finally, the protocols for groups G ( $N = 6$  pairs) and H ( $N = 6$  pairs) followed those of groups E and F, but subordinates were given an implant of cocoa butter alone as a control for the handling and stress associated with implant administration.

*Measurement of CTmax.* Measurement of CTmax was carried out between 9 am and 11 am on pairs of trout in their behaviour tank to achieve consistency and to avoid further handling. Fish were subjected to a linear increase in water temperature of  $0.33 \pm 0.01^\circ\text{C min}^{-1}$  (Becker & Genoway, 1979) until LOE. The temperature of LOE, indicated by the fish turning dorso-ventrally and being unable to right itself within 3 s, was noted as CTmax. Once CTmax was reached, water temperature was returned to the acclimation temperature ( $13^\circ\text{C}$ ). The fish that first reached its CTmax was temporarily removed from the behaviour tank to immediately begin the return to acclimation temperature. Water temperature (measured using a digital thermometer) was altered using a series 440 Fotopanel thermostatic mixing valve (POWERST<sup>TM</sup>, Burlington,

ON), and water flowing to the experimental tanks was vigorously aerated using an equilibration column to ensure maintenance of air saturation with increasing temperature (tested by monitoring dissolved oxygen levels during a CT<sub>max</sub> trial). The CT<sub>max</sub> trials on fish instrumented with heart rate biologgers (see Experiment 2 below) revealed that body temperature (as measured by the bilogger) lagged water temperature by  $\sim 0.3 \pm 0.1^\circ\text{C}$ . Therefore, CT<sub>max</sub> values based on water temperature likely over-estimated actual CT<sub>max</sub> values. Importantly, CT<sub>max</sub> values for dominant and subordinate fish were always determined simultaneously for size-matched pairs of fish held in the same tank such that any differences between dominant and subordinate fish were robust.

*Administration of cortisol implants.* Subordinate rainbow trout were given an intraperitoneal implant of cocoa butter (NOW Health Group Inc., Bloomingdale, IL, USA) containing cortisol (hydrocortisone 21-hemisuccinate, Sigma Aldrich;  $65 \text{ mg kg}^{-1}$  body weight; BW; groups E and F) or cocoa butter alone ( $5 \text{ ml kg}^{-1}$  BW; groups G and H) as a sham control (Pickering & Duston, 1983; Lawrence et al., 2019). The cortisol dose was chosen on the basis of a pilot trial to achieve circulating cortisol concentrations typical of subordinate fish. Cortisol-impregnated cocoa butter implants were prepared by dissolving the hydrocortisone 21-hemisuccinate in 99% ethanol; the cortisol-ethanol solution was added to melted cocoa butter and the ethanol was evaporated off by heating the solution (Hoogenboom et al., 2011; Lawrence et al., 2019). To administer the implants, fish were lightly anaesthetized as described above and liquid cocoa butter ( $\sim 32^\circ\text{C}$ ) was injected into the peritoneal cavity using a 22 G sterile needle and 1 ml syringe, where it quickly solidified. After administration of the implant, fish were returned to their behaviour tanks with the divider inserted to separate the dominant and subordinate fish for the 2 d recovery period.

*Blood sample collection and analysis.* For collection of blood samples, the members of a pair were together lightly anesthetized as described above and 0.3 ml of blood was withdrawn from the caudal vasculature using a 23 G needle and syringe rinsed with 0.5 M ethylenediaminetetraacetic acid (EDTA). Blood samples were collected within 2-3 min of netting the fish to avoid handling-induced elevation of cortisol (Lawrence et al. 2018). The fish were then returned to their tank, separated by the opaque divider, until both individuals had regained equilibrium, upon which the divider was removed (groups A and B) or left in place (groups C-H) until the experiment was terminated. Blood samples were centrifuged at 10,000 g for 2 min, and plasma was flash frozen in liquid N<sub>2</sub> and stored at -80°C for later analysis of cortisol concentrations.

Plasma cortisol concentrations were analyzed using a commercial radioimmunoassay (RIA; MP Biomedical, LLC, USA) previously validated for analysis of trout plasma samples (Gamperl et al., 1994). The intra- and inter-assay coefficients of variation were 4.1% and 3.5%, respectively.

*Heart tissue collection and analysis.* Fish of groups A and B were euthanized by terminal anaesthesia (0.5 g L<sup>-1</sup> ethyl-p-aminobenzoate), and the heart was dissected out. The hearts of fish from group A were blotted dry and the bulbus arteriosus and atrium were removed, after which the mass of the ventricle was measured. Ventricles were sectioned longitudinally using a fresh razor blade and a 20 mm section was fixed in 4% paraformaldehyde overnight at 4°C. The remainder of the ventricle was flash frozen in liquid N<sub>2</sub> and stored at -80°C for later analysis of transcript abundance by real-time RT-PCR or protein abundance by western blot analysis. Fixed ventricle tissue was dehydrated in 70% ethanol and stored in 70% ethanol at 4°C until

histological analysis (see Experiment 3). Ventricle tissue from group B fish was flash frozen in liquid N<sub>2</sub> and stored at -80°C for later analysis of HSP70 abundance by western blotting.

Soluble protein was extracted from frozen ventricle tissue that was ground to a powder on dry ice using a mortar and pestle. Approximately 10-30 mg of powdered ventricle tissue was sonicated (Sonic Dismembrator Model 100, Fisher Scientific) in a RIPA buffer containing protease inhibitors. Sample protein concentrations were determined using the bicinchoninic acid method (BCA; Sigma Aldrich) with bovine serum albumin (BSA; Sigma Aldrich) as a standard. Samples of extracted soluble protein were diluted 2x with Laemmli buffer (Sigma Aldrich) and boiled at 95°C for 5 min. Protein samples (15 µg) were separated by size on 10% polyacrylamide gels and then transferred onto Immuno-Blot LF PVDF membranes (Bio-rad; St- Laurent, QC,CA) using a semi-dry transfer apparatus (Trans-blot® SD; Bio-Rad). Membranes were blocked with 5% skim milk in Tris-buffered saline containing 0.1% Tween 20 (TBST) for 1 h at room temperature, and then incubated overnight at 4°C with primary antibody (1:50,000 rabbit anti-salmon inducible HSP70; Cedarlane AS05061, Burlington, ON, CA) in 2% skim milk in TBST. The following day, membranes were washed with TBST (3x for 5 min each time) and then incubated with secondary antibody (1:5000 goat anti-rabbit IgG conjugated to horseradish peroxidase, HRP, in 2% skim milk in TBST) for 1 h at room temperature. Membranes were washed with TBST (3x for 15 min each time) to remove excess antibody, incubated with 1 ml of Luminata Classico HRP substrate (MilliporeSigma™; Oakville, ON, CA), and imaged using chemiluminescence (ChemiDoc XRS+, Bio-Rad). Relative HSP70 abundance was normalized to total protein using ImageLab 6.0 according to Taylor and Posch (2014).

## Experiment 2

To complement previous work on the responses of dominant and subordinate trout to acute warming (LeBlanc et al. 2011) and further explore potential mechanisms underlying differences in CT<sub>max</sub>,  $f_H$  data and ECG recordings were collected from dominant, subordinate and sham-treated trout during the 4-d social interaction period and the subsequent CT<sub>max</sub> trial. The protocol was similar to that for Group A of Experiment 1 (Fig. S1), but used fish fitted with heart rate loggers and tissue samples were not collected. Following the 20-h recovery period,  $f_H$  measurements were collected every 5 min for 2 h from 9 am (recording frequency = 150 Hz). The divider was removed at 11 am, allowing the members of a pair to interact, and  $f_H$  measurements and ECG recordings were collected every 5 min for 3 h during the initial stages of hierarchy formation. For the next 3 d,  $f_H$  (but not ECG traces) was recorded at 5 min intervals every morning for 2 h, from 9 to 11 am, a period that coincided with the morning observation period. On the morning of day 5, paired and sham fish were subjected to a CT<sub>max</sub> trial (as described above) during which temperature,  $f_H$  and ECG recordings were collected every 3 min. Fish were then euthanized using terminal anaesthesia.

Measurements of  $f_H$  were also carried out on hearts isolated from a separate group of dominant and subordinate trout ( $N = 6$  pairs; see Table 1). This trial served to assess intrinsic  $f_H$  of the heart itself and the capacity for  $f_H$  to increase in response to stimulation, to investigate whether differences in  $f_H$  responses to temperature between dominant and subordinate fish (see Results) reflected effects at the level of the heart itself versus nervous control of  $f_H$ . Fish were euthanized by anaesthetic overdose on day 5. The intact heart was removed from the fish and placed in a thermostatted (to 13°C) bath of Ringer's solution (in mM, 150 NaCl, 2.5 KCl, 1.5 MgSO<sub>4</sub>, 0.4 NaH<sub>2</sub>PO<sub>4</sub>, 10 Glucose, 10 HEPES, 1 CaCl<sub>2</sub>, pH 7.7 at room temperature). The bath

contained two tin-copper electrodes that were ~2 cm apart and connected to a custom-built amplifier that allowed the electrical activity of the heart to be recorded (without direct contact) via a data acquisition system (BIOPAC Systems; Harvard Apparatus Canada, Montreal, QC) and software (AcqKnowledge, BIOPAC Systems; sampling rate set to 200 Hz). A cannula (PE 90 polyethylene tubing; Clay-Adams) was inserted into the ventricle lumen through the bulbus arteriosus and secured in place with 2-0 surgical silk. The cannula was connected to a syringe pump (model KDS220, kdScientific, Holliston, MA, USA) that retrograde perfused the heart with aerated, 13°C Ringer's solution at a rate of 0.05 ml min<sup>-1</sup>, which preliminary experiments established was necessary to maintain heart viability. Following a 10 min recovery period, recording commenced for a 10 min control period. Noradrenaline (a general adrenergic receptor agonist) was then added to the bath to achieve 1 µM final (nominal) concentration and recording continued for an additional 10 min. Heart rate (in beats per minute, bpm) was calculated from 10 s periods of the ECG trace at 5 min (control period) or 1 min (post-noradrenaline addition) intervals.

### Experiment 3

The goal of this experiment was to determine whether the elevation of circulating cortisol levels caused by chronic social stress elicits cardiac hypertrophy and fibrosis in subordinate rainbow trout. To assess cardiac hypertrophy, ventricle weight and thickness of the compact myocardium were measured together with transcript abundances of commonly used markers of muscle growth (Johansen et al., 2011, 2017; Keen et al., 2016, 2017; Nørstrud et al., 2018), including ventricular myosin heavy chain (*vmhc*), slow myosin light chain 2 (*smlc2*), and muscle LIM protein (*mlp*), and the pro-hypertrophic factor regulator of calcineurin I (*rcan1*). To

evaluate fibrotic remodelling, histological assessment of collagen deposition was carried out, and collagen type I protein abundance was measured together with transcript abundance of the collagen type I isoforms, collagen type I alpha 1 (*colla1*), alpha 2 (*colla2*), and alpha 3 (*colla3*). Transcript abundances of the connective tissue regulators, matrix metalloproteinase 2 (*mmp2*), matrix metalloproteinase 9 (*mmp9*), and tissue inhibitor of metalloproteinases 2 (*timp2*) also were measured (Johnson et al., 2014; Johnston et al., 2019). Transcript abundances of the corticosteroid receptors, mineralocorticoid receptor (*mr*) and glucocorticoid receptors 1 and 2 (*gr1* and *gr2*), were measured to assess the potential for the ventricle to respond to cortisol.

*Histological assessment of cardiac collagen abundance.* Fixed ventricle tissue from the fish of group A was embedded in paraffin wax and sectioned transversely at 5 µm thickness to yield approximately 6-10 sections per heart. Sections were placed on positively charged microscope slides (Fisherbrand™ Superfrost™ Plus; Fisher Scientific) and heated at 65°C for 30 min. The paraffin was removed through a series of xylene washes (3x for 5 min), and the tissue was rehydrated using a series of ethanol washes (100%, 95%, 80% for 1 min each). Sections were stained for collagen using Picosirius red (Fisher 5030077) as described by Johnson et al., (2014), and then rinsed with acetic acid.

The stained heart sections were examined using brightfield light microscopy (Axiophot; Zeiss, North York, ON, CA). Three randomly selected areas of one section per heart were photographed, and average relative collagen content was quantified as the area of red staining (indicating collagen presence) within the total area of tissue. In addition, compact myocardium thickness was estimated as the mean of five measurements per image. All image analysis was carried out using Image J (<https://imagej.nih.gov/ij/>) by an observer who was blind to the social status of the fish from which the heart tissue was collected.

*Measurement of transcript abundances by real-time RT-PCR.* Ventricles from the fish of group A stored at -80°C were ground to a powder on dry ice using a mortar and pestle. To extract total RNA, powdered ventricle tissue (approximately 10-40 mg) was sonicated (Sonic Dismembrator Model 100, Fisher Scientific) on ice in TRIzol® reagent (Invitrogen, Carlsbad, CA, USA) according to the manufacturer's protocol. The quantity and quality of RNA were assessed using a NanoDrop® (NanoDrop™ 2000, ThermoFisher Scientific). Following genomic DNA removal, cDNA was synthesized from total RNA using the QuantiTect® reverse transcription kit (Qiagen, Montreal, QC, CA) according to the manufacturer's directions. Gene-specific primer sequences were identified from the literature for target genes as well as *β-actin* as a housekeeping gene (Table S1). Real-time RT-PCR was carried out using the Rotor-Gene SYBR Green PCR kit (Qiagen) and a Rotor-Gene Q real-time PCR machine (Qiagen). Reactions were carried out according to the manufacturer's instructions, but volumes were scaled to 10 µl. Samples were run in duplicate, together with negative controls (a no-template sample in which cDNA was replaced with water, and a no-RT sample in which the cDNA synthesis reaction was carried out without reverse transcriptase). Cycling conditions were as follows: 5 min at 95°C, 42 cycles of 10 s at 95°C, 10 s at 60°C and 10 s at 72°C, followed by melt curve analysis, as per the manufacturer's instructions. Standard curves were generated using serially diluted pooled samples and relative transcript abundances were calculated according to Pfaffl (2001).

*Measurement of protein abundance by western blotting.* Collagen type I protein abundance was measured in ventricle tissue from the fish of group A by western analysis according to the protocol described above using 40 µg of protein sample and 1:1000 rabbit anti-salmon collagen type 1 (Cedarlane CL50171AP, Burlington, ON, CA) as the primary antibody.

*Ex vivo passive pressure-volume curves.* In addition to the histological analysis and measurements of transcript or protein abundance, a functional measure of fibrotic remodelling was obtained by generating *ex vivo* pressure-volume curves. Data were generated for a separate group of pairs ( $N = 8$ ; see Table 1) following the 4-d interaction period. The basic approach of Keen et al. (2016) was used. Intact hearts isolated from the dominant and subordinate fish making up a pair were placed in 19°C Ringer's solution containing 20 mM 2,3-butanedione monoxime (BDM; Sigma-Aldrich) to prevent cardiac contraction. A cannula (PE 90 tubing; Clay-Adams) was inserted through the bulbus arteriosus into the lumen of the ventricle and tied in place with 2-0 surgical silk around the bulbus-ventricle junction. The atrial-ventricular junction was closed with 2-0 silk to seal the ventricle. The cannula was attached to a syringe pump (model KDS220, kdScientific), while a sidearm constructed from PE 50 tubing (Instech Laboratories, Plymouth Meeting, PA) was connected to a pressure transducer (TSD104A, BIOPAC Systems). The pressure transducer was connected to a data acquisition system (BIOPAC Systems, AcqKnowledge software, sampling rate = 200 Hz), and was calibrated daily against a static column of water. The ventricle was filled at a rate of  $0.02 \text{ ml min}^{-1}$  with Ringer's solution containing BDM until its maximum capacity was reached (as determined by a drop in pressure as the ventricle developed a leak).

#### *Data processing and statistical analysis*

Electrocardiogram traces,  $f_H$  and temperature data were obtained from the biologgers using Mercury software (Star Oddi). The ECG traces were used to verify whether  $f_H$  data were reliable, and to identify the temperature at which arrhythmia first occurred. Only individuals with acceptable ECG traces were included in analyses. To be deemed acceptable, a clear P wave and

QRS complex were present, and the quality index (QI0 to QI3; where QI0 = great and QI3 = poor) generated automatically by the Mercury software was <3. Although inclusion of QI1 and QI2 values can increase variability in the  $f_H$  data, inclusion of only QI0 values substantially reduces the data available for analysis (Brijs et al. 2019). Finally,  $f_H$  values below 20 bpm or above 150 bpm at 13°C were eliminated based on the range of  $f_H$  reported in the literature (Wood et al., 1979; Farrell et al., 1996; Farrell, 2002; Sandblom & Axelsson, 2007; Gamperl et al., 2011; Verhille et al., 2013; Ekström et al., 2014, 2018); these cut-off values were adjusted according to temperature using a  $Q_{10}$  value of 2.1 (Gamperl et al. 2011). For the 4-d interaction period,  $f_H$  was reported as the mean value for an individual over the 2 or 3 h measurement period for each day. For the CTmax trial,  $f_H$  at 13°C was calculated as the mean of  $f_H$  values for water temperatures of 13-13.5°C, immediately prior to thermal ramping. Peak  $\Delta f_H$  was the largest difference between  $f_H$  observed during acute warming and  $f_H$  at 13°C.

All statistical analyses were carried out using R-studio (<https://rstudio.com/>). Data were checked for normality using the Kolmogorov–Smirnov test and for equal variances using Levene’s test. In all cases,  $\alpha$  was set to 0.05. In most cases (CTmax, ventricle mass, compact myocardium thickness, collagen deposition, protein and transcript abundances), Student’s *t*-tests were used to determine the statistical significance of differences between dominant and subordinate fish. Where sham-treated fish were included in the experiment, analysis of variance (ANOVA) was used. Plasma cortisol concentrations were analyzed by two-way ANOVA using status (dominant or subordinate) and whether the fish underwent a CTmax trial or not as factors. Heart rate during the interaction period was analyzed by two-way repeated measures (RM) ANOVA with social status (dominant, subordinate or sham) as a between-subject factor and time (day) as a within-subject factor. Heart rate during the CTmax trial was analyzed by linear

regression for each group separately (dominant, subordinate, sham), with comparisons of slopes between dominant and subordinate fish by analysis of covariance (ANCOVA). Heart rates for isolated hearts were analyzed by two-way RM ANOVA with social status (dominant or subordinate) and time (baseline or post-noradrenaline) as factors. Pressure-volume curves were analyzed by two-way RM ANOVA on rank-transformed data with social status (dominant or subordinate) and volume as factors.

## Results

### *Experiment 1: Impact of elevated cortisol on the CTmax of subordinate rainbow trout*

Rainbow trout held in pairs formed social hierarchies in which dominant fish were distinguished from subordinate fish by their behaviour (Table 1). The CTmax of subordinate fish was significantly lower than that of dominant fish (Fig. 1A; Student's *t*-test,  $P = 0.015$ ). Following the physical separation of the fish in a pair for a 48 h recovery period, the CTmax of (recovering) subordinates was similar to that of dominant fish (Fig. 1B; Student's *t*-test,  $P = 0.35$ ). Cortisol treatment of recovering subordinates using a cortisol-containing cocoa butter implant prevented the recovery of thermal tolerance; CTmax in cortisol-treated recovering subordinates was significantly lower than that of dominant fish (Fig. 1C; Student's *t*-test,  $P = 0.0003$ ). The CTmax of sham-treated recovering subordinates, which received a cocoa butter implant lacking cortisol, did not differ from that of dominant fish (Fig. 1D; Student's *t*-test,  $P = 0.2$ ).

Plasma cortisol levels were significantly higher in subordinate than dominant fish after a 4 d interaction period (Fig. 2A; 2-way ANOVA; status  $P = 0.001$ , acute warming  $P < 0.0001$ , status x acute warming  $P = 0.289$ ), but returned to baseline levels after a 48 h recovery period (Fig. 2B; 2-way ANOVA; status  $P = 0.271$ , acute warming  $P < 0.0001$ , status x acute warming  $P = 0.089$ ). Cortisol levels of cortisol-treated recovering subordinates were significantly higher than those of dominant fish (Fig. 2C; 2-way ANOVA; status  $P = 0.0009$ , acute warming  $P = 0.01$ , status x acute warming  $P = 0.62$ ). However, when recovering subordinates were treated with cocoa butter alone, cortisol levels returned to baseline values within the 48 h recovery period (Fig. 2D; 2-way ANOVA; status  $P = 0.0009$ , acute warming  $P = 0.01$ , status x acute warming  $P = 0.62$ ). In all treatment groups, plasma cortisol levels after a CTmax trial were significantly higher than those in fish that had not undergone a CTmax trial, regardless of social status. No difference in HSP70 protein abundance in the heart was detected between subordinate and dominant trout following exposure to acute warming in a CTmax trial (normalized HSP70 abundance =  $1.00 \pm 0.70$  for dominants,  $0.61 \pm 0.48$  for subordinates, mean  $\pm$  SEM,  $N = 6$ ; Student's  $t$ -test,  $P = 0.29$ ).

### *Experiment 2: Heart rate during social interactions and acute warming*

Fish instrumented with  $f_H$  biologgers and held in pairs formed social hierarchies in which dominant fish were distinguished from subordinate fish by their behaviour (Table 1). Measurement of  $f_H$  during social interactions revealed a significant interaction between the effects of time and social status (Fig. 3; 2-way RM ANOVA,  $P = 0.184$  for status,  $P < 0.001$  for time,  $P = 0.020$  for status x time). Heart rate differed among sham, dominant and subordinate fish only on day 2 of the interaction period, where  $f_H$  in sham-treated fish was significantly lower

than that in subordinate fish. Among all groups,  $f_H$  decreased over the interaction period, being significantly higher on day 1 following removal of the divider than on days 3 or 4.

On day 5,  $f_H$  values prior to warming were similar to values for day 4 and did not differ among dominant, subordinate and sham fish (Fig. 4A; one-way ANOVA,  $P = 0.475$ ). During acute warming,  $f_H$  increased with temperature in all groups (Fig. 5). Regressions of  $f_H$  on temperature were significant, with the slope at which heart rate increased with warming being significantly lower in subordinate relative to dominant trout (ANCOVA,  $P = 0.040$ ). Although there were no significant differences in the magnitude of the  $f_H$  response (Fig. 4B; one-way ANOVA,  $P = 0.850$ ), there was a trend for the temperature of peak  $f_H$  response to be lower in subordinate than dominant or sham-treated trout (Fig. 4C; one-way ANOVA,  $P = 0.077$ ).

Similarly, arrhythmia was first detected in subordinate trout at significantly lower temperatures than in dominant or sham-treated trout (Fig. 4D; one-way ANOVA,  $P = 0.002$ ).

Correspondingly, CTmax of subordinate trout ( $26.5 \pm 0.9$ ,  $N = 9$ ) was significantly lower than that of sham-treated fish ( $28.2 \pm 0.1$ ,  $N = 6$ ), although the difference between subordinate and dominant fish ( $27.8 \pm 0.2$ ,  $N = 9$ ) did not quite reach statistical significance (one-way ANOVA on ranks,  $P = 0.012$ ; Student's  $t$ -test on subordinate vs dominant fish,  $P = 0.093$ ).

For isolated hearts, neither baseline  $f_H$  (dominant  $63.0 \pm 3.7$ , subordinate  $60.3 \pm 2.0$ , mean  $\pm$  SEM,  $N = 6$ ) nor peak  $f_H$  post noradrenaline addition (dominant  $70.0 \pm 3.7$ , subordinate  $71.0 \pm 2.4$ ,  $N = 6$ ) differed significantly between dominant and subordinate fish (2-way RM ANOVA on log-transformed data,  $P = 0.878$  for status,  $P < 0.001$  for sample time,  $P = 0.183$  for status x time). The fish from which hearts were isolated formed pairs with divergent behaviour (Table 1) and cortisol concentrations (dominant [cortisol] =  $4.7 \pm 2.1$  ng mL<sup>-1</sup>, subordinate [cortisol] =  $137.6 \pm 43.9$  ng mL<sup>-1</sup>,  $N = 14$  pairs; Student's  $t$ -test,  $P = 0.006$ ).

### *Experiment 3: Does cardiac remodelling occur in subordinate rainbow trout?*

To examine the potential for cardiac remodelling in response to the elevated cortisol of chronic social stress, transcript abundances of the three cortisol receptors in rainbow trout, *gr1*, *gr2* and *mr*, were assessed in the ventricle of dominant versus subordinate trout after 5 d of social interaction (Table 2). No significant differences were detected, although *gr2* exhibited a trend towards higher transcript abundance in subordinate fish (Student's *t*-tests,  $P = 0.53$ ,  $0.062$ ,  $0.71$  for *gr1*, *gr2* and *mr*, respectively). Subordinate fish did not differ from dominant fish in ventricle mass (Fig. 6A; Student's *t*-test,  $P = 0.21$ ) or thickness of the compact myocardium (Fig. 6B; Student's *t*-test,  $P = 0.78$ ). Because the 5-d interaction period (Fig. S1) might not have been long enough for ventricular hypertrophy to become apparent at the organ level, transcript abundances of known molecular markers for hypertrophy were assessed in ventricular tissue (Table 2). The markers *mlp*, *smlc2*, and *vmhc* are associated with muscle growth and are direct indicators of hypertrophy. The marker *rcan1* activates the calcineurin-NFAT signalling cascade, which promotes hypertrophic growth, and is considered a pathological marker of hypertrophy (Keen et al., 2018). Although *rcan1* transcript abundance tended to be higher in the ventricle of subordinate relative to dominant trout (Student's *t*-test,  $P = 0.075$ ), no significant differences were detected (Student's *t*-tests,  $P = 0.39$  for *mlp*,  $0.37$  for *smlc2*, and  $0.55$  for *vmhc*).

Histological assessment of ventricular collagen content using Picrosirius red revealed lower collagen content in subordinate than dominant trout, a difference that did not quite reach statistical significance (Fig. 7A; Student's *t*-test,  $P = 0.062$ ). To further explore this trend, collagen type I protein levels and transcript abundances were evaluated together with transcript abundances of two matrix metalloproteinases (*mmp*) and their inhibitor (*timp2*) involved in

collagen degradation (Table 3). Type I collagen is the major contributor to total collagen content in mammalian hearts (Medugorac, 1982) and in fish is composed of three alpha-helical chains,  $\alpha 1$ ,  $\alpha 2$  and  $\alpha 3$  (Keen et al. 2016). However, neither type I collagen protein abundance (Student's *t*-test,  $P = 0.80$ ) nor transcript abundances of the three alpha-helical chains, *colla1*, *colla2* and *colla3* (Student's *t*-tests,  $P = 0.41, 0.25, 0.27$ , respectively), differed between the ventricles of dominant and subordinate trout. Similarly, no significant differences in the transcript abundances of *mmp2*, *mmp9* and *timp2* were detected (Student's *t*-tests,  $P = 0.55, 0.78, 0.15$ , respectively). Additionally, no differences were detected in the passive stiffness of the ventricle, which was assessed as a functional measure of potential differences in collagen deposition (Fig. 7D; 2-way RM ANOVA; status  $P = 0.812$ , volume  $P < 0.001$ , status x volume  $P = 0.472$ ).

## Discussion

The results of the present study identified cortisol as a major contributor to the lowered CTmax in rainbow trout experiencing chronic social stress. Although CTmax is known to be modulated by factors such as acclimation temperature (e.g. Beitinger and Bennett, 2000; Fangué, 2006; Zhang and Kieffer, 2014; Nyboer and Chapman, 2018), body size (Zhang and Kieffer 2014), life history stage (Komoroske et al. 2014), and chronic social stress (LeBlanc et al. 2011), the physiological mechanisms underlying these effects often remain unclear. Thus, the results of the present study constitute an important step forward in understanding how CTmax is modulated by chronic stress. However, additional work is needed to identify the mechanisms linking changes in CTmax to circulating cortisol levels. Because chronic cortisol elevation can induce pathological ventricular hypertrophy with associated negative impacts on cardiac function in rainbow trout (Johansen et al. 2011, 2017), the present study assessed markers of ventricular

hypertrophy and fibrosis, and  $f_H$  responses to acute warming in subordinate trout. The results of these experiments did not support chronic social stress-induced cardiac remodelling as a mechanism underlying the effects of cortisol on CTmax.

### *Effects of cortisol on CTmax*

The findings of the present study support the hypothesis that prolonged elevation of cortisol in subordinate rainbow trout lowers thermal tolerance. As reported by LeBlanc et al. (2011), the CTmax of subordinate trout was significantly lower than that of dominant fish after 4 d of interaction. In recovering subordinates that were allowed to recover from social stress for 48 h by placing a partition in the tank to separate the members of a pair, cortisol levels were on par with those of dominant fish, in agreement with the findings of Culbert and Gilmour (2016). The lowering of cortisol levels in recovering subordinates was accompanied by a return of CTmax to values similar to those in dominant fish. A similar recovery of both CTmax and cortisol levels was observed in recovering subordinates treated with sham implants (i.e. cocoa butter alone). Compellingly, however, when the fall in cortisol levels was prevented by treating recovering subordinates with cortisol, CTmax also failed to recover. Collectively, these data indicate that elevated cortisol is a key driver contributing to lower CTmax in trout exposed to chronic social stress. To our knowledge, no other study has focused specifically on cortisol as a modulator of CTmax in fish, but there is support in the literature for stress-induced changes in CTmax. For example, threadfin shad (*Dorosoma petenense*) showed reduced thermal tolerance (lower CTmax) shortly after being subjected to a netting stressor (Monirian et al., 2010), a protocol that would be expected to elicit a cortisol response (Strange et al., 1977; Øverli et al., 1999a; Jeffrey et al., 2014). Exposure to hypoxia (Rutledge & Beitinger 1989; Healy & Schulte 2012), as well

as acute changes in salinity (Shaughnessy & McCormick 2018), also have been associated with reductions in CT<sub>max</sub>, although in these cases it is more difficult to link changes in CT<sub>max</sub> to cortisol specifically. A related observation that is also consistent with cortisol-mediated changes in thermal tolerance is that in a field study carried out in their natural habitat, cortisol-treated checkered pufferfish (*Sphoeroides testudineus*) selected cooler temperatures than control animals (Cull et al., 2015).

The mechanisms through which chronic elevation of cortisol during social stress reduces CT<sub>max</sub> remain to be determined. Acute warming elevates circulating cortisol levels in rainbow trout and other fishes (Pérez-Casanova et al., 2008; LeBlanc et al., 2011, 2012; Yang et al., 2018; Yusishen et al., 2020) and factors that attenuate this heat-induced cortisol response potentially could impair thermal tolerance. Chronic social stress was associated with attenuation of the cortisol response to handling or netting stressors (Øverli et al., 1999a; Jeffrey et al., 2014; Culbert & Gilmour, 2016). However, subordinate trout in the present study mounted cortisol responses to acute warming that were comparable to those of dominant fish, a finding also reported by LeBlanc et al. (2011). The lower CT<sub>max</sub> of subordinate relative to dominant fish despite comparable cortisol responses to acute warming suggests that the cortisol response to acute warming does not influence thermal tolerance. This conclusion is supported by a recent study of lake sturgeon (*Acipenser fulvescens*), where the cortisol response to acute warming was reduced in sturgeon held in groups vs singly, but CT<sub>max</sub> was unchanged (Yusishen et al., 2020). Similarly, CT<sub>max</sub> values for HR and LR (low cortisol responsiveness to a standardized stressor) trout did not differ despite strongly divergent cortisol responses to acute warming (LeBlanc et al. 2012).

Measurement of  $f_H$  provided additional insight into the physiological responses to acute warming of subordinate vs dominant fish. The expected increase in  $f_H$  with increasing temperature (Farrell et al., 1996; Clark et al., 2008; Steinhausen et al., 2008; Gamperl et al., 2011) was apparent in all groups, with the magnitude of the  $f_H$  increase being comparable across dominant, subordinate and sham-treated trout. However, peak increases in  $f_H$  tended to occur at higher temperatures in dominant and sham-treated trout than in subordinate trout, resulting in a significant difference between dominant and subordinate trout in the slope of the relationship between  $f_H$  and temperature. That is, dominant fish appeared to be able to maintain increases in  $f_H$  to higher temperatures than subordinate fish. Thus, increases in  $f_H$  tended to plateau or peak near the  $CT_{max}$  regardless of social status, with peak  $f_H$  and  $CT_{max}$  values in subordinate trout being lower than those in dominant or sham-treated trout. This pattern is in agreement with observations more broadly of peak  $f_H$  responses coinciding with the upper thermal limit (Ekström et al., 2014, 2017, 2019; Gilbert et al., 2019). Correspondingly, irregularities in the electrical activity of the heart occurred at significantly lower temperatures in subordinate than dominant or sham-treated trout. Recent work suggests that rising temperature alters the electrical excitability of the trout heart, ultimately disrupting the frequency of heart beats (Vornanen, 2016, 2020; Haverinen & Vornanen, 2020). In particular, it appears that at high temperature, the ventricle fails to rhythmically contract in response to the atrium owing to an atrioventricular (AV) block. The AV block is caused by reduced excitability in the ventricle, which, in turn, reflects differential changes in  $Na^+$  and  $K^+$  conductance with temperature (Vornanen et al., 2014; Vornanen, 2016; Badr et al., 2018; Haverinen and Vornanen, 2020, reviewed by Vornanen, 2020). Whether the prolonged elevation of cortisol experienced by subordinate fish directly contributes to changes in cardiac ion conductances that alter the temperature sensitivity of the

ventricle, or whether changes in cardiac ion conductances are an indirect effect of the actions of cortisol elsewhere remains to be determined. In this regard, it is worth considering that the cardiac HSP70 response to acute warming was similar in dominant and subordinate fish, even though subordinate fish were exposed to a lower temperature (by virtue of their lower CT<sub>max</sub>) than dominant fish.

Additional work clearly is needed to identify the mechanisms through which chronic elevation of cortisol during social stress reduces CT<sub>max</sub>. Given that the endpoint of a CT<sub>max</sub> trial is loss of motor function/equilibrium (Beitinger et al., 2000), effects of temperature on brain neural function may determine CT<sub>max</sub>. Recent support for this possibility was provided by Jutfelt et al. (2019), who reported that CT<sub>max</sub> in Atlantic cod (*Gadus morhua*) could be increased, albeit to a limited extent, by local cooling of the brain. The fish brain is rich in both the mineralocorticoid (MR) and glucocorticoid receptors (GR1 and GR2) that mediate the physiological effects of cortisol on target tissues, making it very responsive to changes in cortisol (Teitsma et al., 1998; Alderman & Vijayan, 2012; Alderman et al., 2012; Teles et al., 2013; Kiilerich et al., 2018). Further, experimental elevation of cortisol levels as well as the chronic elevation of cortisol associated with social stress reduce neurogenesis in the brain of rainbow trout, providing an additional mechanism through which cortisol may influence nervous function (Sørensen et al., 2011, 2012; Johansen et al., 2012). Thus, effects of cortisol on brain neural function warrant consideration as a mechanism through which chronic elevation of cortisol may impair thermal tolerance in fishes. Further study is needed to directly manipulate cortisol levels as well as explore the impacts of stressors beyond social stress that chronically elevate cortisol.

### *Chronic social stress and cardiac remodelling*

Support for the hypothesis that subordinate trout experience cardiac remodelling was limited. Neither ventricle mass nor thickness of the compact myocardium was elevated in subordinate fish, unlike the situation in HR rainbow trout (Johansen et al. 2011) or trout treated with cortisol for 21-45 d (Johansen et al. 2017; Norstrud et al. 2018). Because cortisol treatment for shorter periods altered the transcript abundance of molecular markers of hypertrophic signalling and remodelling without significantly affecting ventricle mass (Norstrud et al. 2018), several of these markers were compared between dominant and subordinate trout. Transcript abundances of slow myosin light chain 2 (*smlc2*), ventricular myosin heavy chain (*vmhc*), muscle LIM protein (*mlp*), and regulator of calcineurin 1 (*rcan1*) did not differ significantly between dominant and subordinate trout, although ventricles from subordinate trout tended to show higher transcript abundance of *rcan1*. Transcript abundances of the cortisol receptors *gr1*, *gr2* and *mr* did not differ between the ventricles of dominant and subordinate trout, suggesting that the capacity for cortisol signalling was maintained in the heart of subordinate trout. Thus, it seems likely that a longer exposure to elevated cortisol than the 5 d interaction period of the present study is needed to elicit ventricular hypertrophy.

In the HR rainbow trout studied by Johansen et al. (2011), ventricular hypertrophy was accompanied by an increase in collagen content that resulted in a more fibrotic heart, a situation associated with increased risk of dysfunction. The hearts of cold-acclimated trout are both larger and have greater collagen content than the hearts of warm-acclimated trout, although in this case the cardiac remodelling is not viewed as pathological (Graham and Farrell 1989; Klaiman et al. 2011; Keen et al., 2016). In contrast to our prediction, histological analysis of ventricle tissue sections revealed a tendency for lower collagen content in the hearts of subordinate relative to

dominant trout. However, this difference was not accompanied by differences in collagen type I protein or transcript abundances, nor were differences detected in the transcript abundances of collagen regulators. The apparent fall in collagen abundance in subordinate fish therefore may represent a change in collagen organization from densely packed (which appears red when stained with Picrosirius red and viewed under polarized light) to thin and/or disorganized (Rich & Whittaker, 2005).

Indices of cardiac function also were assessed in subordinate rainbow trout. In cold-acclimated trout, the higher collagen content of the heart increases stiffness (Keen et al., 2016). Based on ventricular pressure-volume relationships for isolated hearts, subordinate and dominant fish did not differ in passive stiffness of the ventricle, a finding that is consistent with the lack of difference in collagen type I protein abundance. Similarly, neither baseline  $f_H$  nor the  $f_H$  response to adrenergic stimulation differed between the isolated hearts of dominant and subordinate fish. Somewhat unexpectedly, given previous reports of elevated  $f_H$  in subordinate trout (Thomas and Gilmour 2012), *in vivo*  $f_H$  also did not differ between dominant and subordinate trout in the present study. The use of  $f_H$  loggers in the present study enabled effects of hierarchy formation on  $f_H$  to be evaluated. Previous studies of  $f_H$  responses to social interaction were limited to a single fish observing another of known social status, because non-invasive approaches that could not differentiate between individuals were used to measure  $f_H$  (Höjesjö et al., 2007, 2015). In the present study,  $f_H$  decreased significantly by day 2 in both sham and dominant fish from a high reached on day 1 after removal of the divider in the tank, but  $f_H$  was slightly slower to decrease in subordinate fish, perhaps suggesting greater metabolic expenditure in these fish during the early stages of hierarchy establishment.

Although 5 d of social stress had little effect on cardiac structure or function in the present study, it is possible that different results would be obtained if sexually mature fish were examined rather than the juvenile trout used in the present study. For example, Klaiman et al. (2011) reported stronger effects of cold acclimation on heart morphology in male versus female rainbow trout, and attributed the differences to the pro-hypertrophic effects of testosterone versus the anti-hypertrophic effects of estrogen. Thus, the resilience of cardiac structure and function to the effects cortisol in subordinate trout of the present study may reflect, at least in part, the use of juvenile fish. Longer exposure to cortisol than the 5 d interaction period of the present study appears to be necessary to induce ventricular hypertrophy in juvenile salmonids (Johansen et al. 2011; Johansen et al. 2017; Nørstrud et al. 2018).

### **Acknowledgements**

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery and Research Tools & Instruments grants to KMG, and NSERC and Canada Foundation for Innovation grants to SJC. BB was supported by Ontario graduate scholarships (OGS) and a scholarship from Fonds de recherche de Québec (Nature et technologies). MJL was supported by OGS and NSERC scholarships. Thanks are extended to the aquatics facility staff for their excellent care of the rainbow trout.

## References

- Alderman, S. L. and Vijayan, M. M.** (2012).  $11\beta$ -hydroxysteroid dehydrogenase type 2 in zebrafish brain: A functional role in hypothalamus-pituitary-interrenal axis regulation. *J. Endocrinol.* **215**, 393–402.
- Alderman, S. L., McGuire, A., Bernier, N. J. and Vijayan, M. M.** (2012). Central and peripheral glucocorticoid receptors are involved in the plasma cortisol response to an acute stressor in rainbow trout. *Gen. Comp. Endocrinol.* **176**, 79–85.
- Badr, A., Korajoki, H., Abu-Amra, E.-S., Mohamed, El-Sayed, F. and Vornanen, M.** (2018). Effects of seasonal acclimatization on thermal tolerance of inward currents in roach (*Rutilus rutilus*) cardiac myocytes. *J. Comp. Physiol. B* **188**, 255–269.
- Becker, C. D. and Genoway, R. G.** (1979). Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. *Env. Biol. Fish* **4**, 245–256.
- Beers, J. M. and Sidell, B. D.** (2011). Thermal tolerance of Antarctic notothenioid fishes correlates with level of circulating hemoglobin. *Physiol. Biochem. Zool.* **84**, 353–362.
- Beitinger, T. L. and Bennett, W. A.** (2000). Quantification of the role of acclimation temperature in temperature tolerance of fishes. *Environ. Biol. Fishes* **58**, 277–288.
- Beitinger, T., Bennett, W. and McCauley, R.** (2000). Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. *Environ. Biol. Fishes* **58**, 237–275.
- Blasco, F. R., Esbaugh, A. J., Killen, S. S., Rantin, F. T., Taylor, E. W. and McKenzie, D. J.** (2020). Using aerobic exercise to evaluate sub-lethal tolerance of acute warming in fishes. *J. Exp. Biol.* **223**, jeb218602.

- Brijs, J., Sandblom, E., Rosengren, M., Sundell, K., Berg, C., Axelsson, M. and Gräns, A.** (2019). Prospects and pitfalls of using heart rate bio-loggers to assess the welfare of rainbow trout (*Oncorhynchus mykiss*) in aquaculture. *Aquaculture* **509**, 188-197.
- Clark, T. D., Sandblom, E., Cox, G. K., Hinch, S. G. and Farrell, A. P.** (2008). Circulatory limits to oxygen supply during an acute temperature increase in the Chinook salmon (*Oncorhynchus tshawytscha*). *Am. J. Physiol. Integr. Comp. Physiol.* **295**, 1631–1639.
- Cull, F., Suski, C. D., Shultz, A., Danylchuk, A. J., O'Connor, C. M., Murchie, K. J. and Cooke, S. J.** (2015). Consequences of experimental cortisol manipulations on the thermal biology of the checkered puffer (*Sphoeroides testudineus*) in laboratory and field environments. *J. Therm. Biol.* **47**, 63–74.
- Culbert, B. M. and Gilmour, K. M.** (2016). Rapid recovery of the cortisol response following social subordination in rainbow trout. *Physiol. Behav.* **164**, 306–313.
- Devor, D. P., Kuhn, D. E., O'Brien, K. M. and Crockett, E. L.** (2016). Hyperoxia does not extend critical thermal maxima (CT<sub>max</sub>) in white-or red-blooded Antarctic notothenioid fishes. *Physiol. Biochem. Zool.* **89**, 1–9.
- DiBattista, J. D., Levesque, H. M., Moon, T. W. and Gilmour, K. M.** (2006). Growth depression in socially subordinate rainbow trout *Oncorhynchus mykiss* : More than a fasting effect. *Physiol. Biochem. Zool.* **79**, 675–687.
- Ejike, C. and Schreck, C. B.** (1980). Stress and social hierarchy rank in coho salmon. *Trans. Am. Fish. Soc.* **109**, 423–426.
- Ekström, A., Jutfelt, F. and Sandblom, E.** (2014). Effects of autonomic blockade on acute thermal tolerance and cardioventilatory performance in rainbow trout, *Oncorhynchus mykiss*. *J. Therm. Biol.* **44**, 47–54.

- Ekström, A., Hellgren, K., Gräns, A., Pichaud, N. and Sandblom, E.** (2016). Dynamic changes in scope for heart rate and cardiac autonomic control during warm acclimation in rainbow trout. *J. Exp. Biol.* **219**, 1106–9.
- Ekström, A., Axelsson, M., Gräns, A., Brijs, J. and Sandblom, E.** (2017). Influence of the coronary circulation on thermal tolerance and cardiac performance during warming in rainbow trout. *Am. J. Physiol. Integr. Comp. Physiol.* **312**, R549–R558.
- Ekström, A., Axelsson, M., Gräns, A., Brijs, J. and Sandblom, E.** (2018). Importance of the coronary circulation for cardiac and metabolic performance in rainbow trout (*Oncorhynchus mykiss*). *Biol. Lett.* **14**, 20180063.
- Ekström, A., Gräns, A. and Sandblom, E.** (2019). Can't beat the heat? Importance of cardiac control and coronary perfusion for heat tolerance in rainbow trout. *J. Comp. Physiol. B* **189**, 757–769.
- Ern, R., Norin, T., Gamperl, A. K. and Esbaugh, A. J.** (2016). Oxygen dependence of upper thermal limits in fishes. *J. Exp. Biol.* **219**, 3376–3383.
- Ern, R., Johansen, J. L., Rummer, J. L. and Esbaugh, A. J.** (2017). Effects of hypoxia and ocean acidification on the upper thermal niche boundaries of coral reef fishes. *Biol. Lett.* **13**, 20170135.
- Fangue, N. A.** (2006). Intraspecific variation in thermal tolerance and heat shock protein gene expression in common killifish, *Fundulus heteroclitus*. *J. Exp. Biol.* **209**, 2859–2872.
- Fangue, N. A., Osborne, E. J., Todgham, A. E. and Schulte, P. M.** (2011). The onset temperature of the heat-shock response and whole-organism thermal tolerance are tightly correlated in both laboratory-acclimated and field-acclimatized tidepool sculpins. *Physiol. Biochem. Zool.* **84**, 341–352.

- Farrell, A.** (2002). Cardiorespiratory performance in salmonids during exercise at high temperature: insights into cardiovascular design limitations in fishes. *Comp. Biochem. Physiol. Part A Mol. Integr. Physiol.* **132**, 797–810.
- Farrell, A. P., Gamperl, A. K., Hicks, J. M. T., Shiels, H. A. and Jain, K. E.** (1996). Maximum cardiac performance of rainbow trout (*Oncorhynchus mykiss*) at temperatures approaching their upper lethal limit. *J. Exp. Biol.* **199**, 663–672.
- Gamperl, A.K., Swafford, B. L. and Rodnick, K. J.** (2011). Elevated temperature, per se, does not limit the ability of rainbow trout to increase stroke volume. *J. Therm. Biol.* **36**, 7–14.
- Gamperl, A. K., Vijayan, M. M. and Boutilier, R. G.** (1994). Experimental control of stress hormone levels in fishes: techniques and applications. *Rev. Fish Biol. Fish.* **4**, 215–255.
- Gilbert, M. J. H., Rani, V., McKenzie, S. M. and Farrell, A. P.** (2019). Autonomic cardiac regulation facilitates acute heat tolerance in rainbow trout: in situ and in vivo support. *J. Exp. Biol.* **222**, jeb194365.
- Gilmour, K. M., DiBattista, J. D. and Thomas, J. B.** (2005). Physiological causes and consequences of social status in Salmonid Fish. *Integr. Comp. Biol.* **45**, 263–273.
- Gilmour, K. M., Kirkpatrick, S., Massarsky, A., Pearce, B., Saliba, S., Lise, C.-É., Thomas, S. and Moon, W.** (2012). The influence of social status on hepatic glucose metabolism in rainbow trout *Oncorhynchus mykiss*. *Physiol. Biochem. Zool.* **85**, 309–320.
- Gollock, M. J., Currie, S., Petersen, L. H. and Gamperl, A. K.** (2006). Cardiovascular and haematological responses of Atlantic cod (*Gadus morhua*) to acute temperature increase. *J. Exp. Biol.* **209**, 2961–2970.
- Graham, M. S. and Farrell, A.P.** (1989). The effect of temperature acclimation and adrenaline on the performance of a perfused trout heart. *Physiol. Zool.* **62**, 38-61.

- Haverinen, J. and Vornanen, M.** (2020). Reduced ventricular excitability causes atrioventricular block and depression of heart rate in fish at critically high temperatures. *J. Exp. Biol.* **223**, jeb225227.
- Höjesjö, J., Andersson, P., Engman, A. and Johnsson, J. I.** (2007). Rapid bystander assessment of intrinsic fighting ability: behavioural and heart rate responses in rainbow trout. *Anim. Behav.* **74**, 1743–1751.
- Höjesjö, J., Axelsson, M., Dahy, R., Gustavsson, L. and Johnsson, J. I.** (2015). Sight or smell? Behavioural and heart rate responses in subordinate rainbow trout exposed to cues from dominant fish. *PeerJ* **3**, e1169.
- Hoogenboom, M. O., Armstrong, J. D., Miles, M. S., Burton, T., Groothuis, T. G. G. and Metcalfe, N. B.** (2011). Implantation of cocoa butter reduces egg and hatchling size in *Salmo trutta*. *J. Fish Biol.* **79**, 587–596.
- Jeffrey, J. D., Gollock, M. J. and Gilmour, K. M.** (2014). Social stress modulates the cortisol response to an acute stressor in rainbow trout (*Oncorhynchus mykiss*). *Gen. Comp. Endocrinol.* **196**, 8–16.
- Jeffries, K. M., Fangue, N. A. and Connon, R. E.** (2018). Multiple sub-lethal thresholds for cellular responses to thermal stressors in an estuarine fish. *Comp. Biochem. Physiol. A* **225**, 33–45.
- Johansen, I. B., Lunde, I. G., Røsjø, H., Christensen, G., Nilsson, G. E., Bakken, M. and Øverli, Ø.** (2011). Cortisol response to stress is associated with myocardial remodeling in salmonid fishes. *J. Exp. Biol.* **214**, 1313–1321.

- Johansen, I. B., Sørensen, C., Sandvik, G. K., Nilsson, G. E., Höglund, E., Bakken, M. and Øverli, Ø.** (2012). Neural plasticity is affected by stress and heritable variation in stress coping style. *Comp. Biochem. Physiol. D* **7**, 161–171.
- Johansen, I. B., Sandblom, E., Skov, P. V., Gräns, A., Ekström, A., Lunde, I. G., Vindas, M. A., Zhang, L., Höglund, E., Frisk, M., et al.** (2017). Bigger is not better: cortisol-induced cardiac growth and dysfunction in salmonids. *J. Exp. Biol.* **220**, 2545–2553.
- Johnson, A. C., Turko, A. J., Klaiman, J. M., Johnston, E. F. and Gillis, T. E.** (2014). Cold acclimation alters the connective tissue content of the zebrafish (*Danio rerio*) heart. *J. Exp. Biol.* **217**, 1868–1875.
- Johnsson, J. I., Winberg, S. and Sloman, K. A.** (2005). Social Interaction. In *Fish Physiology v 24 Behaviour and Physiology of Fish* (eds. Sloman, K. A., Wilson, R. W., Balshine, S., Farrell, A. P. and Brauner, C. J.), pp. 152–195. Academic Press.
- Johnston, E. F., Cadonic, I. G., Craig, P. M. and Gillis, T. E.** (2019). microRNA-29b knocks down collagen type I production in cultured rainbow trout (*Oncorhynchus mykiss*) cardiac fibroblasts. *J. Exp. Biol.* **222**, jeb202788.
- Joyce, W. and Perry, S. F.** (2020). Hypoxia inducible factor-1 $\alpha$  knockout does not impair acute thermal tolerance or heat hardening in zebrafish. *Biol. Lett.* **16**, 20200292.
- Joyce, W. and Wang, T.** (2020). What determines systemic blood flow in vertebrates? *J. Exp. Biol.* **223**, jeb215335.
- Joyce, W., Egginton, S., Farrell, A. P., Crockett, E. L., O'Brien, K. M. and Axelsson, M.** (2018). Exploring nature's natural knockouts: in vivo cardiorespiratory performance of Antarctic fishes during acute warming.

- Jutfelt, F., Norin, T., Ern, R., Overgaard, J., Wang, T., McKenzie, D. J., Lefevre, S., Nilsson, E., Metcalfe, N. B., Hickey, A. J. R., et al.** (2018). Oxygen- and capacity-limited thermal tolerance: blurring ecology and physiology. *J. Exp. Biol.* **221**, jeb169615.
- Jutfelt, F., Roche, D. G., Clark, T. D., Norin, T., Binning, S. A., Speers-Roesch, B., Amcoff, M., Morgan, R., Andreassen, A. H. and Sundin, J.** (2019). Brain cooling marginally increases acute upper thermal tolerance in Atlantic cod. *J. Exp. Biol.* **222**, jeb208249.
- 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.
- Keen, A. N., Klaiman, J. M., Shiels, H. A. and Gillis, T. E.** (2017). Temperature-induced cardiac remodelling in fish. *J. Exp. Biol.* **220**, 147-160.
- Keen, A. N., Fenna, A. J., McConnell, J. C., Sherratt, M. J., Gardner, P. and Shiels, H. A.** (2018). Macro- and micromechanical remodelling in the fish atrium is associated with regulation of collagen 1 alpha 3 chain expression. *Pflügers Arch. J. Physiol.* **470**, 1205–1219.
- Kiilerich, P., Servili, A., Péron, S., Valotaire, C., Goardon, L., Leguen, I. and Prunet, P.** (2018). Regulation of the corticosteroid signalling system in rainbow trout HPI axis during confinement stress. *Gen. Comp. Endocrinol.* **258**, 184–193.
- Klaiman, J. M., Fenna, A. J., Shiels, H. A., Macri, J. and Gillis, T. E.** (2011). Cardiac remodeling in fish: Strategies to maintain heart function during temperature change. *PLoS one* **6**, e24464.

- Kostyniuk, D. J., Culbert, B. M., Mennigen, J. A. and Gilmour, K. M.** (2018). Social status affects lipid metabolism in rainbow trout, *Oncorhynchus mykiss*. *Am. J. Physiol.* **315**, R241–R255.
- Lawrence, M. J., Jain-Schlaepfer, S., Zolderdo, A. J., Algera, D. A., Gilmour, K. M., Gallagher, A. J. and Cooke, S. J.** (2018). Are 3 minutes good enough for obtaining baseline physiological samples from teleost fish? *Can. J. Zool.* **96**, 774-786.
- Lawrence, M. J., Zolderdo, A. J., Godin, J.-G. J., Mandelman, J. W., Gilmour, K. M. and Cooke, S. J.** (2019). Cortisol does not increase risk of mortality to predation in juvenile bluegill sunfish: A manipulative experimental field study. *J. Exp. Zool. Part A Ecol. Integr. Physiol.* **331**, 253–261.
- LeBlanc, S., Middleton, S., Gilmour, K. M. and Currie, S.** (2011). Chronic social stress impairs thermal tolerance in the rainbow trout (*Oncorhynchus mykiss*). *J. Exp. Biol.* **214**, 1721–1731.
- LeBlanc, S., Hoglund, E., Gilmour, K. M. and Currie, S.** (2012). Hormonal modulation of the heat shock response: insights from fish with divergent cortisol stress responses. *Am. J. Physiol.* **302**, R184–R192.
- Lefevre, S., Findorf, I., Bayley, M., Huong, D. T. T. and Wang, T.** (2016). Increased temperature tolerance of the air-breathing Asian swamp eel *Monopterus albus* after high-temperature acclimation is not explained by improved cardiorespiratory performance. *J. Fish Biol.* **88**, 418–432.
- Lutterschmidt, W. I. and Hutchison, V. H.** (1997). The critical thermal maximum: history and critique. *Can. J. Zool.* **75**, 1561–1574.

- Medugorac, I.** (1982). Characterization of intramuscular collagen in the mammalian left ventricle\*). *Basic Res. Cardiol* **77**, 589–598.
- Mendonça, P. C. and Gamperl, A. K.** (2010). The effects of acute changes in temperature and oxygen availability on cardiac performance in winter flounder (*Pseudopleuronectes americanus*). *Comp. Biochem. Physiol. A*. **155**, 245–252.
- Monirian, J., Sutphin, Z. and Myrick, C.** (2010). Effects of holding temperature and handling stress on the upper thermal tolerance of threadfin shad *Dorosoma petenense*. *J. Fish Biol.* **76**, 1329–1342.
- Motyka, R., Norin, T., Petersen, L. H., Huggett, D. B. and Gamperl, A. K.** (2017). Long-term hypoxia exposure alters the cardiorespiratory physiology of steelhead trout (*Oncorhynchus mykiss*), but does not affect their upper thermal tolerance. *J. Therm. Biol.* **68**, 149–161.
- Moutou, K. A., McCarthy, I. D. and Houlihan, D. F.** (1998). The effect of ration level and social rank on the development of fin damage in juvenile rainbow trout. *J. Fish Biol.* **52**, 756–770.
- Muñoz, N. J., Farrell, A. P., Heath, J. W. and Neff, B. D.** (2018). Hematocrit is associated with thermal tolerance and modulated by developmental temperature in juvenile Chinook salmon. *Physiol. Biochem. Zool.* **91**, 757–762.
- Norin, T., Malte, H. and Clark, T. D.** (2014). Aerobic scope does not predict the performance of a tropical eurythermal fish at elevated temperatures. *J. Exp. Biol.* **217**, 244–251.
- Nørstrud, K. S., Vindas, M. A., Nilsson, E. and Johansen, I. B.** (2018). Short-term cortisol exposure alters cardiac hypertrophic and non-hypertrophic signalling in a time-dependent manner in rainbow trout. *Biol. Open* **7**, bio037853.

- Nyboer, E. A. and Chapman, L. J.** (2018). Cardiac plasticity influences aerobic performance and thermal tolerance in a tropical, freshwater fish at elevated temperatures. *J. Exp. Biol.* **221**, jeb178087.
- Øverli, Ø., Harris, C. A. and Winberg, S.** (1999a). Short-term effects of fights for social dominance and the establishment of dominant-subordinate relationships on brain monoamines and cortisol in rainbow trout. *Brain, Behav. Evol.* **54**, 263–275.
- Øverli, Ø., Olsen, R. E., Løvik, F. and Ringø, E.** (1999b). Dominance hierarchies in Arctic charr, *Salvelinus alpinus* L.: differential cortisol profiles of dominant and subordinate individuals after handling stress. *Aquac. Res.* **30**, 259–264.
- Pérez-Casanova, J. C., Afonso, L. O. B., Johnson, S. C., Currie, S. and Gamperl, A. K.** (2008). The stress and metabolic responses of juvenile Atlantic cod *Gadus morhua* L. to an acute thermal challenge. *J. Fish Biol.* **72**, 899–916.
- Pfaffl, M. W.** (2001). A new mathematical model for relative quantification in real-time RT-PCR. *Nucleic Acids Res.* **29**, 2002–2007.
- Pickering, A. D. and Duston, J.** (1983). Administration of cortisol to brown trout, *Salmo trutta* L., and its effects on the susceptibility to *Saprolegnia* infection and furunculosis. *J. Fish Biol* **23**, 163–175.
- Pörtner, H. O.** (2010). Oxygen- And capacity-limitation of thermal tolerance: A matrix for integrating climate-related stressor effects in marine ecosystems. *J. Exp. Biol.* **213**, 881–893.
- Pörtner, H.-O., Bock, C. and Mark, F. C.** (2017). Oxygen-and capacity-limited thermal tolerance: bridging ecology and physiology. *J. Exp. Biol.* **220**, 2685–2696.

- Pottinger, T. G. and Carrick, T. R.** (1999). Modification of the plasma cortisol response to stress in rainbow trout by selective breeding. *Gen. Comp. Endocrinol.* **116**, 122–132.
- Pottinger, T. G. and Pickering, A. D.** (1992). The influence of social interaction on the acclimation of rainbow trout, *Oncorhynchus mykiss* (Walbaum) to chronic stress. *J. Fish Biol.* **41**, 435–447.
- Prystay, T. S., Eliason, E. J., Lawrence, M. J., Dick, M., Brownscombe, J. W., Patterson, D. A., Crossin, G. T., Hinch, S. G. and Cooke, S. J.** (2017). The influence of water temperature on sockeye salmon heart rate recovery following simulated fisheries interactions. *Conserv. Physiol.* **5**, 1–12.
- Rich, L. and Whittaker, P.** (2005). Collagen and picrosirius red staining: A polarized light assessment of fibrillar hue and spatial distribution. *Braz. J. morphol. Sci* **22**, 97–104.
- Sandblom, E. and Axelsson, M.** (2007). Venous hemodynamic responses to acute temperature increase in the rainbow trout (*Oncorhynchus mykiss*). *Am. J. Physiol.* **292**, R2292–R2298.
- Slovan, K. A., Motherwell, G., O'Connor, K. I. and Taylor, A. C.** (2000). The effect of social stress on the standard metabolic rate (SMR) of brown trout, *Salmo trutta*. *Fish Physiol. Biochem.* **23**, 49–53.
- Slovan, K. A., Metcalfe, N. B., Taylor, A. C. and Gilmour, K. M.** (2001). Plasma cortisol concentrations before and after social stress in rainbow trout and brown trout. *Physiol. Biochem. Zool.* **74**, 383–389.
- Sørensen, C., Bohlin, L. C., Øverli, Ø. and Nilsson, G. E.** (2011). Cortisol reduces cell proliferation in the telencephalon of rainbow trout (*Oncorhynchus mykiss*). *Physiol. Behav.* **102**, 518–523.

- Sørensen, C., Nilsson, G. E., Summers, C. H. and Øverli, Ø.** (2012). Social stress reduces forebrain cell proliferation in rainbow trout (*Oncorhynchus mykiss*). *Behav. Brain Res.* **227**, 311–318.
- Sørensen, C., Johansen, I. B. and Øverli, Ø.** (2013). Physiology of social stress in fishes. In *The Physiology of Fishes, Fourth Edition* (eds. Evans, D. H., Claiborne, J. B. and Currie, S.), pp. 288–326. CRC Press.
- Steinhausen, M. F., Sandblom, E., Eliason, E. J., Verhille, C. and Farrell, A. P.** (2008). The effect of acute temperature increases on the cardiorespiratory performance of resting and swimming sockeye salmon (*Oncorhynchus nerka*). *J. Exp. Biol.* **211**, 3915–3926.
- Strange, R. J., Schreck, C. B. and Golden, J. T.** (1977). Corticoid Stress Responses to Handling and Temperature in Salmonids; Corticoid Stress Responses to Handling and Temperature in Salmonids. *Trans. Am. Fish. Soc.* **106**, 213–218.
- Taylor, S. C. and Posch, A.** (2014). The Design of a Quantitative Western Blot Experiment. *Biomed Res. Int.* **2014**, 361590.
- Teitsma, C. A., Anglade, I., Toutirais, G., Muñoz-Cueto, J. A., Saligaut, D., Ducouret, B. and Kah, O.** (1998). Immunohistochemical localization of glucocorticoid receptors in the forebrain of the rainbow trout (*Oncorhynchus mykiss*). *J. Comp. Neurol.* **401**, 395–410.
- Teles, M., Tridico, R., Callol, A., Fierro-Castro, C. and Tort, L.** (2013). Differential expression of the corticosteroid receptors GR1, GR2 and MR in rainbow trout organs with slow release cortisol implants. *Comp. Biochem. Physiol. A* **164**, 506–511.
- Thomas, J. B. and Gilmour, K. M.** (2012). Low social status impairs hypoxia tolerance in rainbow trout (*Oncorhynchus mykiss*). *J. Comp. Physiol. B* **182**, 651–662.

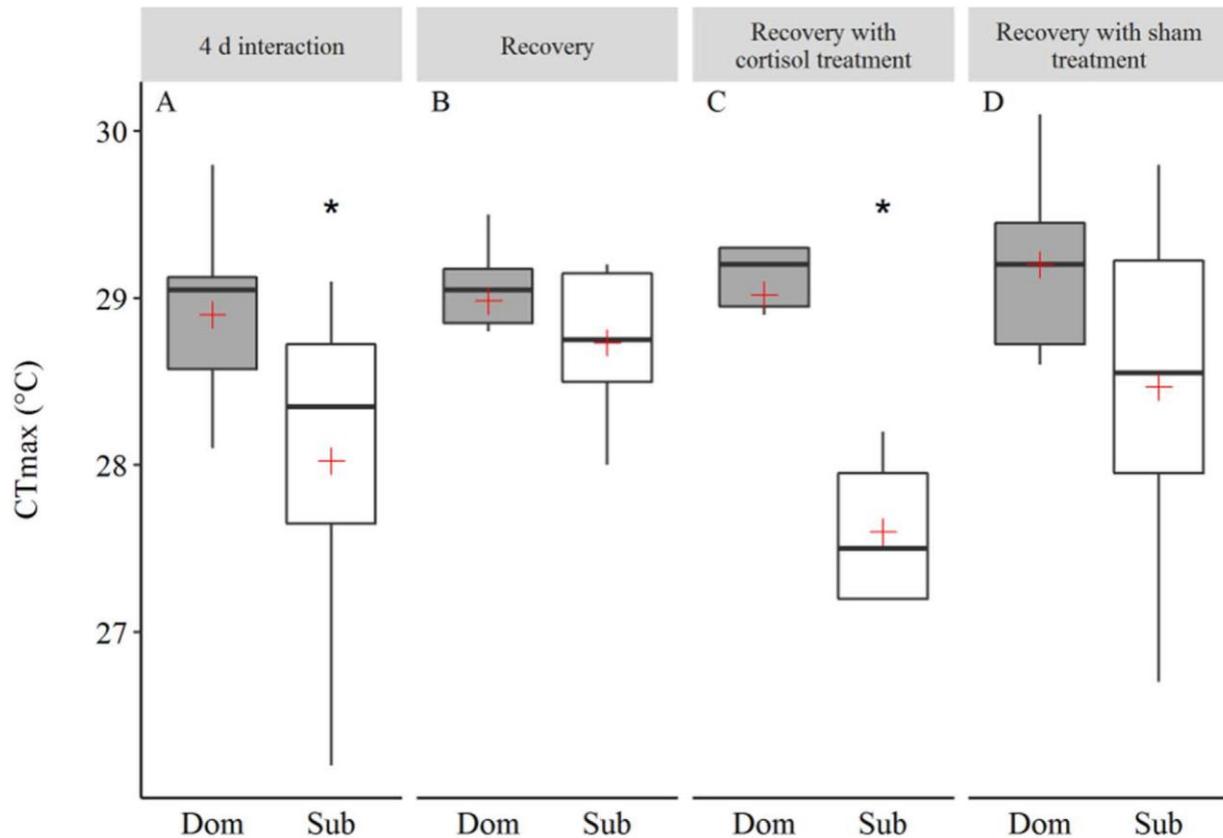
- Verhille, C., Anttila, K. and Farrell, A. P.** (2013). A heart to heart on temperature: Impaired temperature tolerance of triploid rainbow trout (*Oncorhynchus mykiss*) due to early onset of cardiac arrhythmia. *Comp. Biochem. Physiol. A* **164**, 653–657.
- Vornanen, M.** (2016). The temperature dependence of electrical excitability in fish hearts. *J. Exp. Biol.* **219**, 1941–1952.
- Vornanen, M.** (2020). Feeling the heat: source–sink mismatch as a mechanism underlying the failure of thermal tolerance. *J. Exp. Biol.* **223**, jeb225680.
- Vornanen, M., Haverinen, J. and Egginton, S.** (2014). Acute heat tolerance of cardiac excitation in the brown trout (*Salmo trutta fario*). *J. Exp. Biol.* **217**, 299–309.
- Wang, T., Lefevre, S., Iversen, N. K., Findorf, I., Buchanan, R. and McKenzie, D. J.** (2014). Anaemia only causes a small reduction in the upper critical temperature of sea bass: Is oxygen delivery the limiting factor for tolerance of acute warming in fishes? *J. Exp. Biol.* **217**, 4275–4278.
- Winberg, S., Höglund, E. and Øverli, Ø.** (2016). Variation in the Neuroendocrine Stress Response. In *Fish Physiology, v 35 Biology of Stress in Fish* (eds. Schreck, C. B., Tort, L., Farrell, A. P. and Brauner, C. J.), pp. 35–74. Academic Press.
- Wood, C. M., Pieprzak, P. and Trott, D. J. N.** (1979). The influence of temperature and anaemia on the adrenergic and cholinergic mechanisms controlling heart rate in the rainbow trout. *Can. J. Zool.* **57**, 2440–2447.
- Yang, S., Yan, T., Zhao, L., Wu, H., Du, Z., Yan, T. and Xiao, Q.** (2018). Effects of temperature on activities of antioxidant enzymes and  $\text{Na}^+/\text{K}^+$ -ATPase, and hormone levels in *Schizothorax prenanti*. *J. Therm. Biol.* **72**, 155–160.

**Yusishen, M. E., Yoon, G. R., Bugg, W., Je, K. M., Currie, S. and Anderson, W. G. (2020).**

Love thy neighbor : Social buffering following exposure to an acute thermal stressor in a gregarious fish , the lake sturgeon (*Acipenser fulvescens*). *Comp. Biochem. Physiol. A* **243**, 110686.

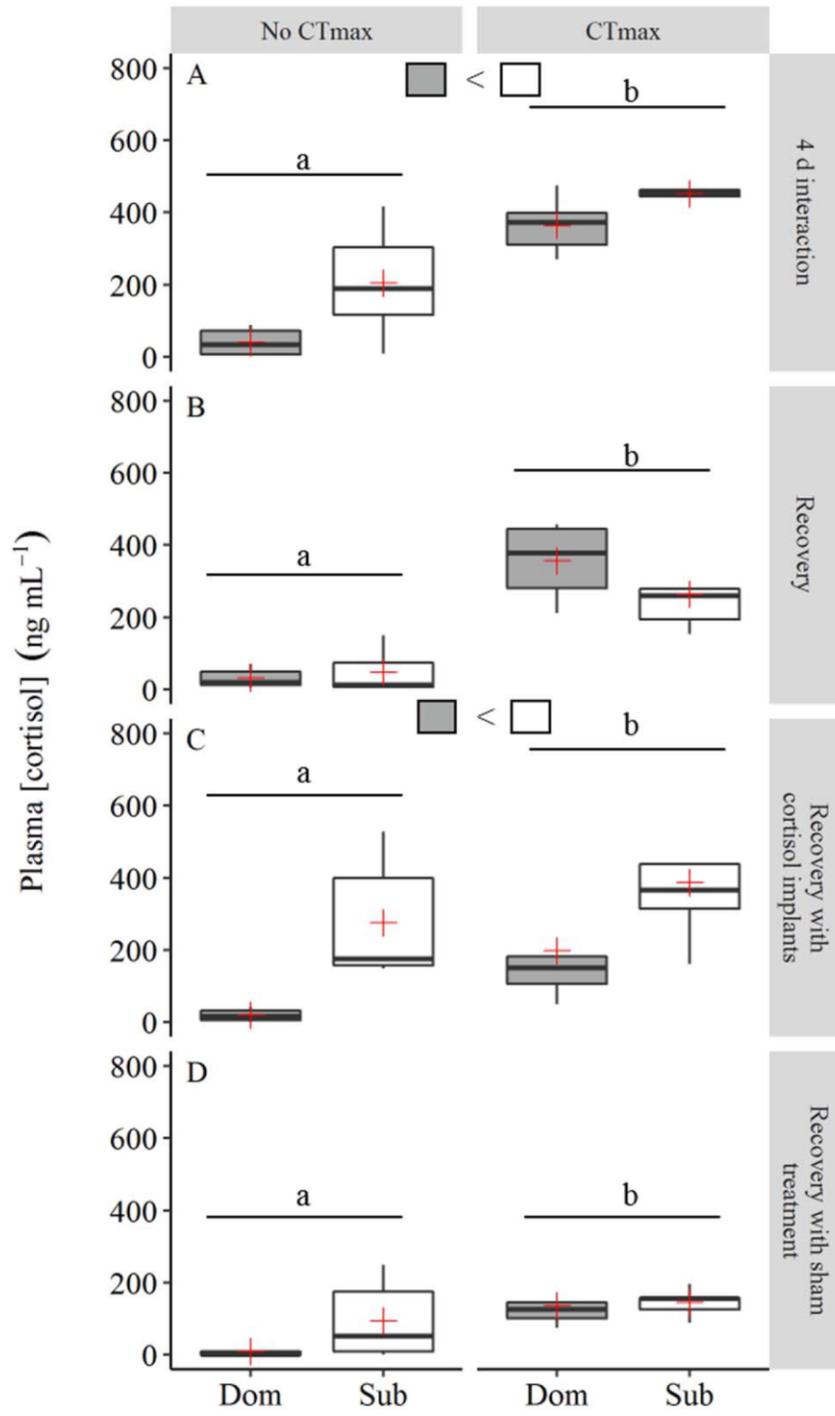
**Zhang, Y. and Kieffer, J. D. (2014).** Critical thermal maximum (CT<sub>max</sub>) and hematology of shortnose sturgeons (*Acipenser brevirostrum*) acclimated to three temperatures. *Can. J. Zool.* **92**, 215–221.

## Figures

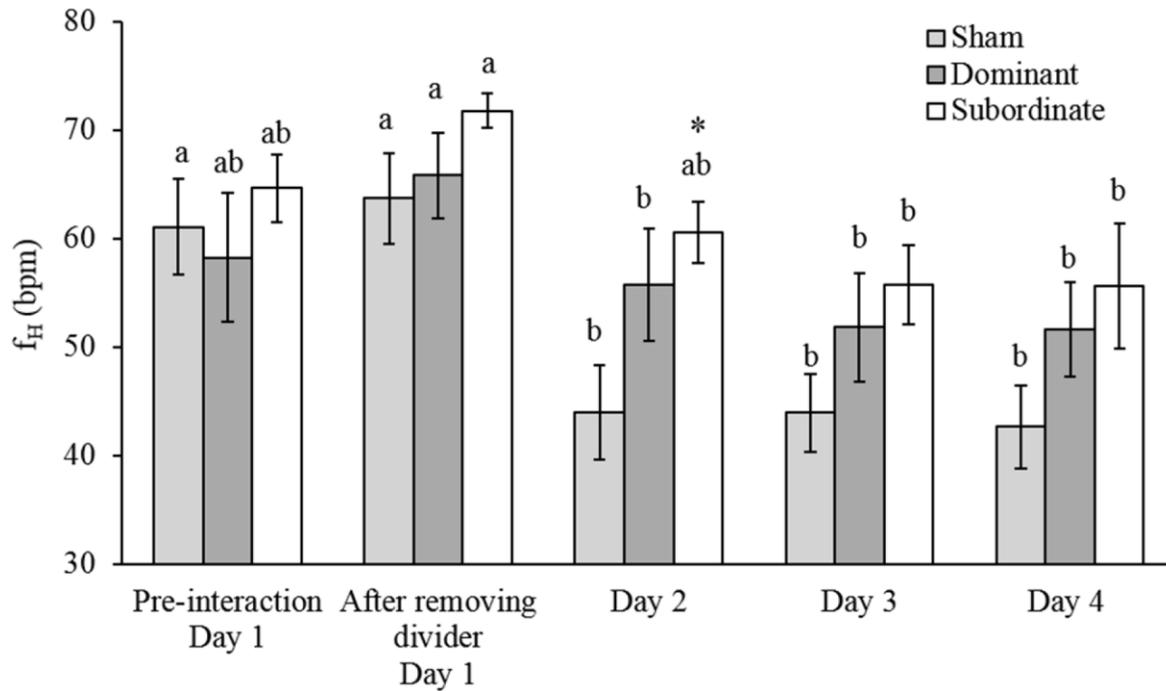


**Figure 1.** Critical thermal maxima (CT<sub>max</sub>) of dominant and subordinate rainbow trout (*Oncorhynchus mykiss*) following (A) social interactions for 4 d ( $N = 12$  pairs), (B) 48 h of recovery from a 4 d social interaction period ( $N = 6$  pairs), (C) 48 h of recovery from 4 d of social interaction but with cortisol treatment of subordinate fish during the recovery period ( $N = 6$  pairs), and (D) 48 h of recovery from 4 d of social interactions but with sham treatment (cocoa butter implant) of subordinate fish during the recovery period ( $N = 6$  pairs). An asterisk indicates a significant difference between dominant and subordinate fish within a treatment group

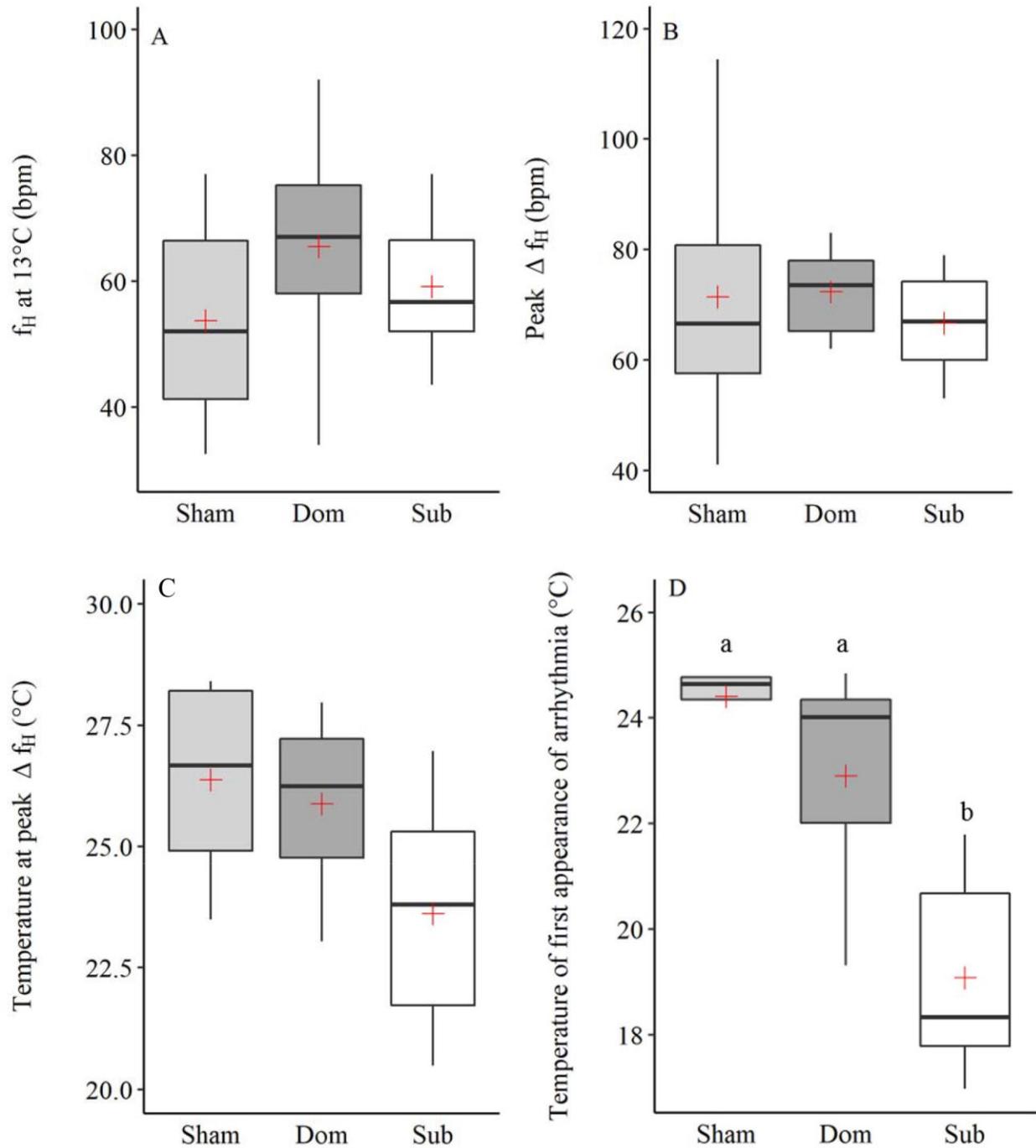
(Student's  $t$ -tests,  $P = 0.015, 0.35, 0.0003$  and  $0.2$  for panels A to D, respectively). Data are presented as box plots where the upper and lower limits of the box indicate the 75<sup>th</sup> and 25<sup>th</sup> percentiles, respectively, the black line across the box indicates the median, the whiskers indicate the maximum and minimum values, and the red plus sign indicates the mean value.



**Figure 2.** Plasma cortisol concentrations of subordinate and dominant rainbow trout (*Oncorhynchus mykiss*) following (A) social interactions for 4 d ( $N = 8$  and 6 pairs; 2-way ANOVA; status  $P = 0.001$ , acute warming  $P < 0.0001$ , status x acute warming  $P = 0.289$ ), (B) 48 h of recovery from a 4 d social interaction period ( $N = 7$  and 6 pairs; 2-way ANOVA; status  $P = 0.271$ , acute warming  $P < 0.0001$ , status x acute warming  $P = 0.089$ ), (C) 48 h of recovery from a 4 d social interaction period with cortisol treatment of subordinate fish during the recovery period ( $N = 6$  and 6 pairs; 2-way ANOVA; status  $P = 0.0009$ , acute warming  $P = 0.01$ , status x acute warming  $P = 0.62$ ), and (D) 48 h of recovery from a 4 d social interaction period with sham treatment of subordinate fish during the recovery period ( $N = 6$  and 5 pairs; 2-way ANOVA; status  $P = 0.09$ , acute warming  $P = 0.006$ , status x acute warming  $P = 0.20$ ). A significant effect of acute warming is indicated by pairs of bars (linked by a horizontal line) that do not share a letter. A significant effect of social status is indicated on the panel using the fill symbols (grey for dominant fish and white for subordinate fish). Data are presented as box plots; please see the legend of Fig. 1 for details.

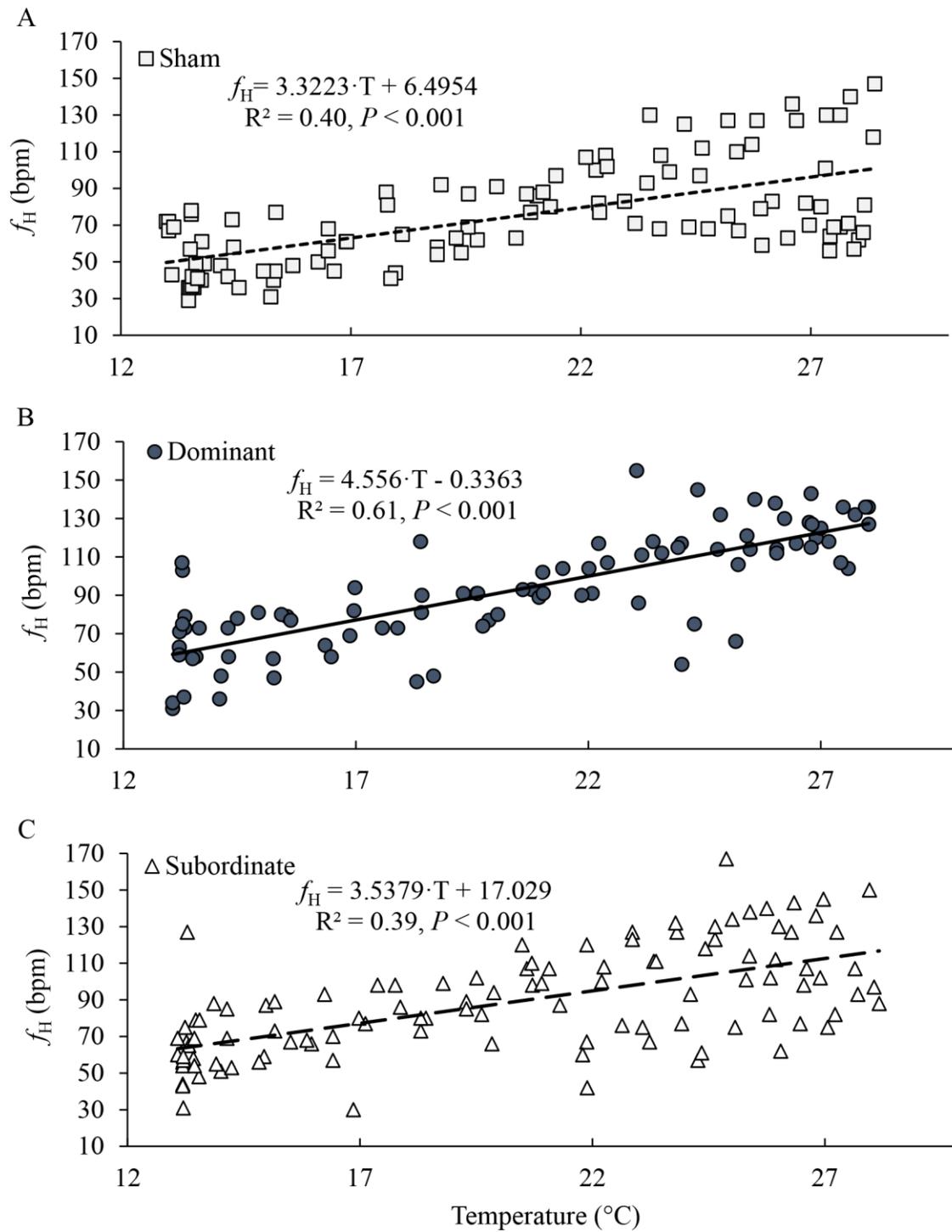


**Figure 3.** Heart rate ( $f_H$ ) of dominant, subordinate and sham rainbow trout (*Oncorhynchus mykiss*) prior to (pre-interaction) and during social interactions. Heart rate was measured using biologgers for a 2 h period each morning except for the period immediately after removal of the divider, where  $f_H$  was collected for 3 h. Values are means  $\pm$  SEM ( $N = 6$  sham, 8 dominant and 8 subordinate fish). Bars that share a letter within a social status category are not significantly different from one another, and within a day, an asterisk indicates a significant difference from the sham fish (2-way RM ANOVA; status  $P = 0.184$ , day  $P < 0.001$ , status  $\times$  day  $P = 0.020$ ).

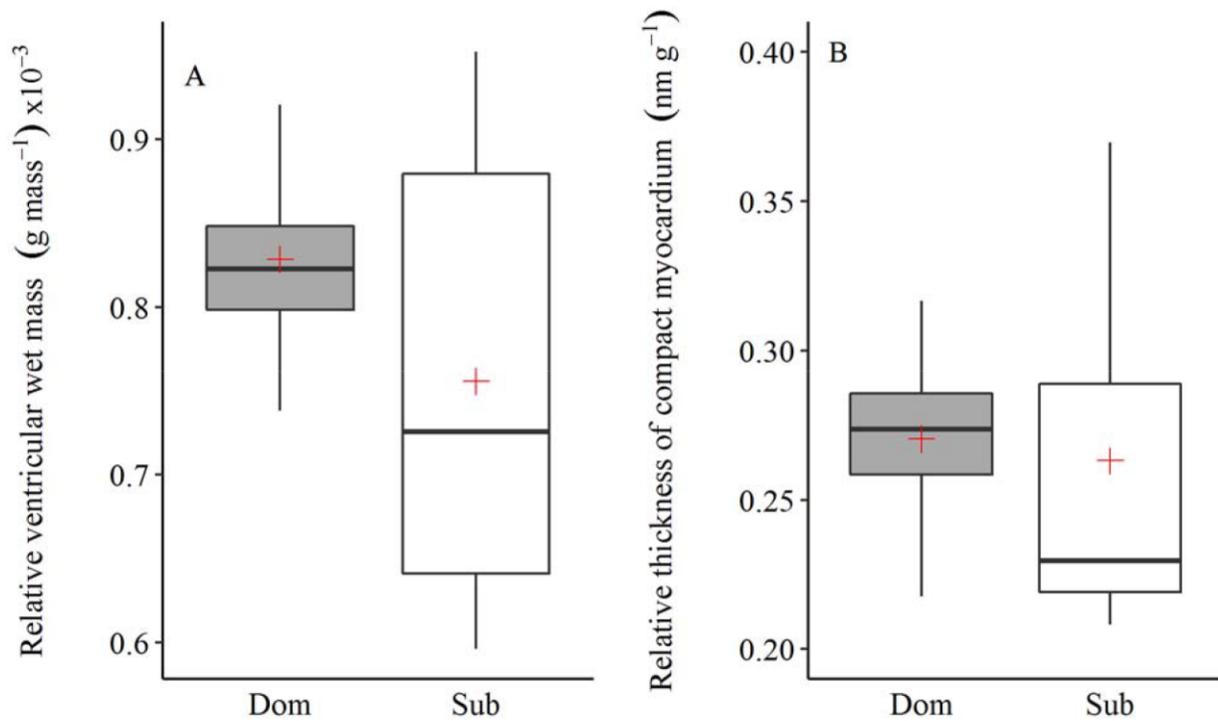


**Figure 4.** Measurements of heart rate ( $f_H$ ) of sham ( $N = 6$ ), dominant ( $N = 6$ ) and subordinate ( $N = 6$ ) rainbow trout (*Oncorhynchus mykiss*) during a CTmax trial. (A)  $f_H$  at 13°C, immediately prior to the CTmax trial, (B) the peak increase in heart rate ( $\Delta f_H$ ), (C) the temperature at which

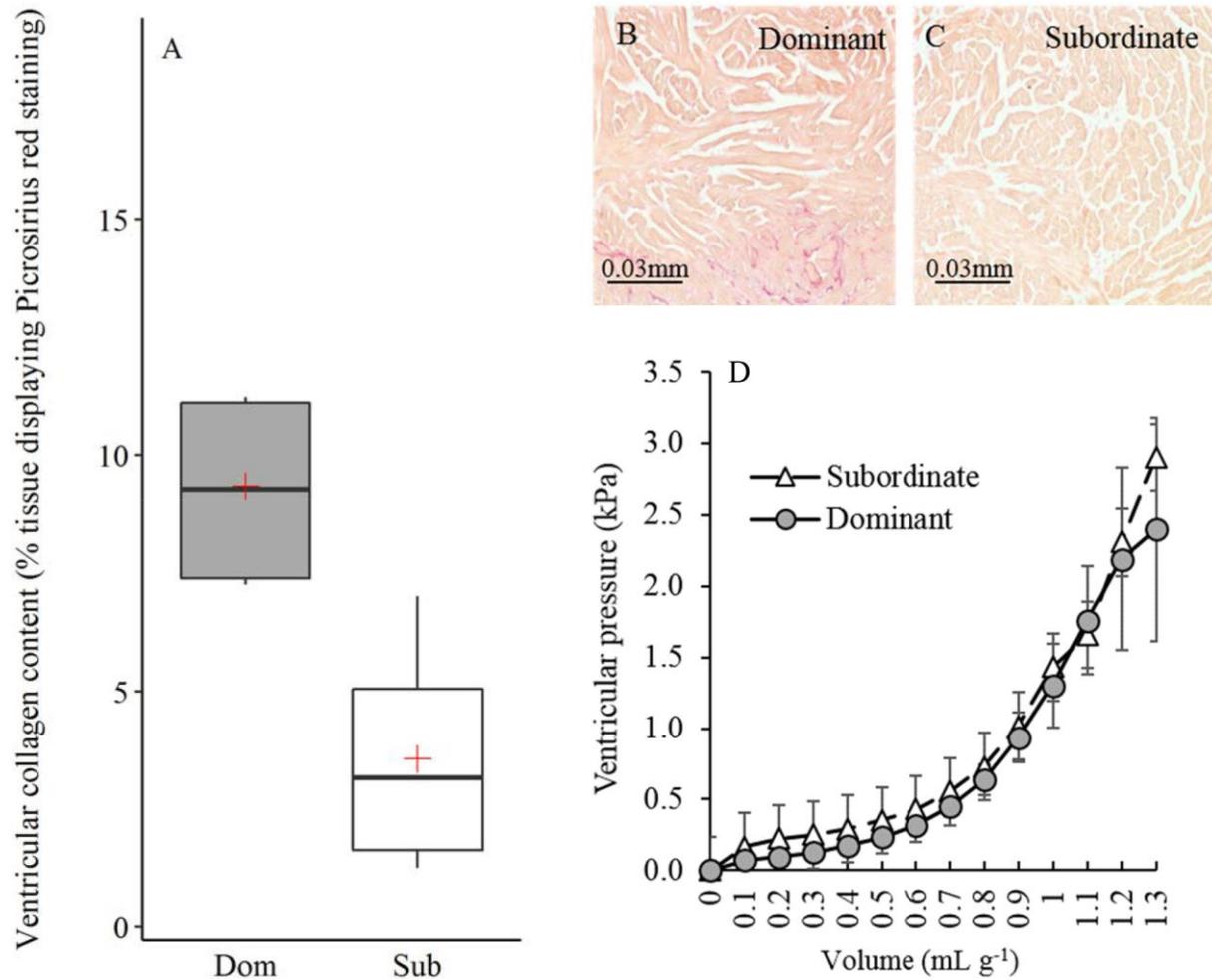
the peak  $\Delta f_H$  occurred, and (D) the temperature at which arrhythmia was first detected in ECG traces. Groups that share a letter are not significantly different from one another (one-way ANOVA;  $P = 0.475, 0.850, 0.077$  and  $0.002$  for panels A to D, respectively). Data are presented as box plots; please see the legend of Fig. 1 for details.



**Figure 5.** Heart rate ( $f_H$ ) of rainbow trout (*Oncorhynchus mykiss*) during acute warming for (A) sham (105 points for  $N = 6$  fish), (B) dominant (89 points for  $N = 6$  fish), and (C) subordinate fish (109 points for  $N = 7$  fish). The equation of the line determined by linear regression is indicated on the plot, together with the  $R^2$  and  $P$  values for the regression.



**Figure 6.** (A) Relative ventricular wet mass of dominant ( $N = 8$ ) and subordinate ( $N = 8$ ) rainbow trout (*Oncorhynchus mykiss*) after 5 d of social interaction. (B) Relative compact myocardial thickness assessed histologically from sections of ventricle tissue stained with Picrosirius red for dominant ( $N = 5$ ) and subordinate ( $N = 5$ ) trout after 5 d of social interaction. Relative mass and relative thickness were standardized using the mass of the individual fish. No significant differences were detected between dominant and subordinate fish (Student's  $t$ -tests,  $P = 0.21$  and  $0.78$  for panels A and B, respectively). Data are presented as box plots; see the legend of Fig. 1 for details.



**Figure 7.** Relative ventricular collagen content assessed histologically from tissue sections stained with Picrosirius red for dominant ( $N = 6$ ) and subordinate ( $N = 6$ ) rainbow trout (*Oncorhynchus mykiss*) after 5 d of social interaction. (A) Collagen content was quantified as the percentage of the tissue in the micrograph showing red staining. The difference between dominant and subordinate fish did not reach statistical significance (Student's  $t$ -test,  $P = 0.062$ ). Data are presented as a box plot; please see the legend of Fig. 1 for details. Representative images of ventricle tissue sections from (B) dominant and (C) subordinate trout stained with Picrosirius red also are presented. (D) Passive pressure-volume relationships for ventricles

isolated from dominant and subordinate fish. Values are means  $\pm$  S.E.M, and each data point represents a mean of  $N \geq 4$  individual fish (maximum 8). Pressure was normalized to start at 0 kPa for graphical representation (as per Keen et al., 2016). Ventricular pressure was significantly affected by volume but not social status (2-way RM ANOVA; status  $P = 0.812$ , volume  $P < 0.001$ , status x volume  $P = 0.472$ ).

**Table 1.** Morphometric data and behaviour scores for dominant and subordinate rainbow trout (*Oncorhynchus mykiss*).

Experimental group	Status	Mass (g)	Fork length (cm)	Behaviour score
<b>4 d interaction (Groups A + B)</b>	Dominant ( $N = 12$ )	$113.5 \pm 6.2$	$21.3 \pm 0.4$	$1.2 \pm 0.4$
	Subordinate ( $N = 12$ )	$110.3 \pm 6.6$	$21.0 \pm 0.4$	$-1.6 \pm 0.2$
<b>Recovery (Groups C + D)</b>	Dominant ( $N = 13$ )	$110.0 \pm 4.4$	$21.5 \pm 0.3$	$1.6 \pm 0.3$
	Subordinate ( $N = 13$ )	$108.8 \pm 5.7$	$21.6 \pm 0.4$	$-1.2 \pm 0.2$
<b>Recovery with cortisol treatment (Groups E + F)</b>	Dominant ( $N = 12$ )	$79.1 \pm 3.8$	$19.1 \pm 0.3$	$1.7 \pm 0.3$
	Subordinate ( $N = 12$ )	$77.4 \pm 3.8$	$19.3 \pm 0.4$	$-1.5 \pm 0.1$
<b>Recovery with sham treatment (Groups G + H)</b>	Dominant ( $N = 12$ )	$90.1 \pm 6.5$	$20.0 \pm 0.6$	$1.4 \pm 0.4$
	Subordinate ( $N = 12$ )	$87.6 \pm 6.6$	$20.0 \pm 0.6$	$-1.6 \pm 0.2$
<b>Heart rate bilogger trial</b>	Sham ( $N = 6$ )	$154 \pm 4.9$	$23.7 \pm 0.3$	NA
	Dominant ( $N = 10$ )	$138.2 \pm 4.9$	$23.3 \pm 0.3$	$1.5 \pm 0.3$
	Subordinate ( $N = 10$ )	$138.2 \pm 5.0$	$23.3 \pm 0.3$	$-1.5 \pm 0.7$
<b>Isolated heart preparations</b>	Dominant ( $N = 14$ )	$121.1 \pm 4.6$	$22.4 \pm 0.3$	$1.5 \pm 0.2$
	Subordinate ( $N = 14$ )	$120.2 \pm 4.1$	$21.8 \pm 0.3$	$-1.5 \pm 0.1$

Values are means  $\pm$  SEM, with  $N$  numbers indicated in parentheses next to social status.

**Table 2.** Relative mRNA abundances of corticosteroid receptors and genes used as indicators of cardiac hypertrophy in the ventricle of subordinate and dominant rainbow trout (*Oncorhynchus mykiss*).

Gene	Dominant (N = 5)	Subordinate (N = 6)	P-value
<b>Corticosteroid receptors</b>			
<i>gr1</i>	1.17 ± 0.31	0.92 ± 0.23	0.53
<i>gr2</i>	1.05 ± 0.16	1.84 ± 0.32	0.062
<i>mr</i>	1.07 ± 0.20	1.16 ± 0.11	0.71
<b>Indicators of cardiac hypertrophy</b>			
<i>vmhc</i>	1.04 ± 0.16	0.89 ± 0.17	0.55
<i>smlc2</i>	1.93 ± 1.09	0.78 ± 0.42	0.37
<i>mlp</i>	1.29 ± 0.38	0.87 ± 0.25	0.39
<i>rca1</i>	1.08 ± 0.20	3.17 ± 0.93	0.075

*gr1*, glucocorticoid receptor 1; *gr2*, glucocorticoid receptor 2; *mr*, mineralocorticoid receptor; *vmhc*, ventricular myosin heavy chain; *smlc2*, slow myosin light chain 2; *mlp*, muscle LIM protein; *rca1*, regulator of calcineurin I

Values are means ± SEM, with N numbers indicated in parentheses below social status.

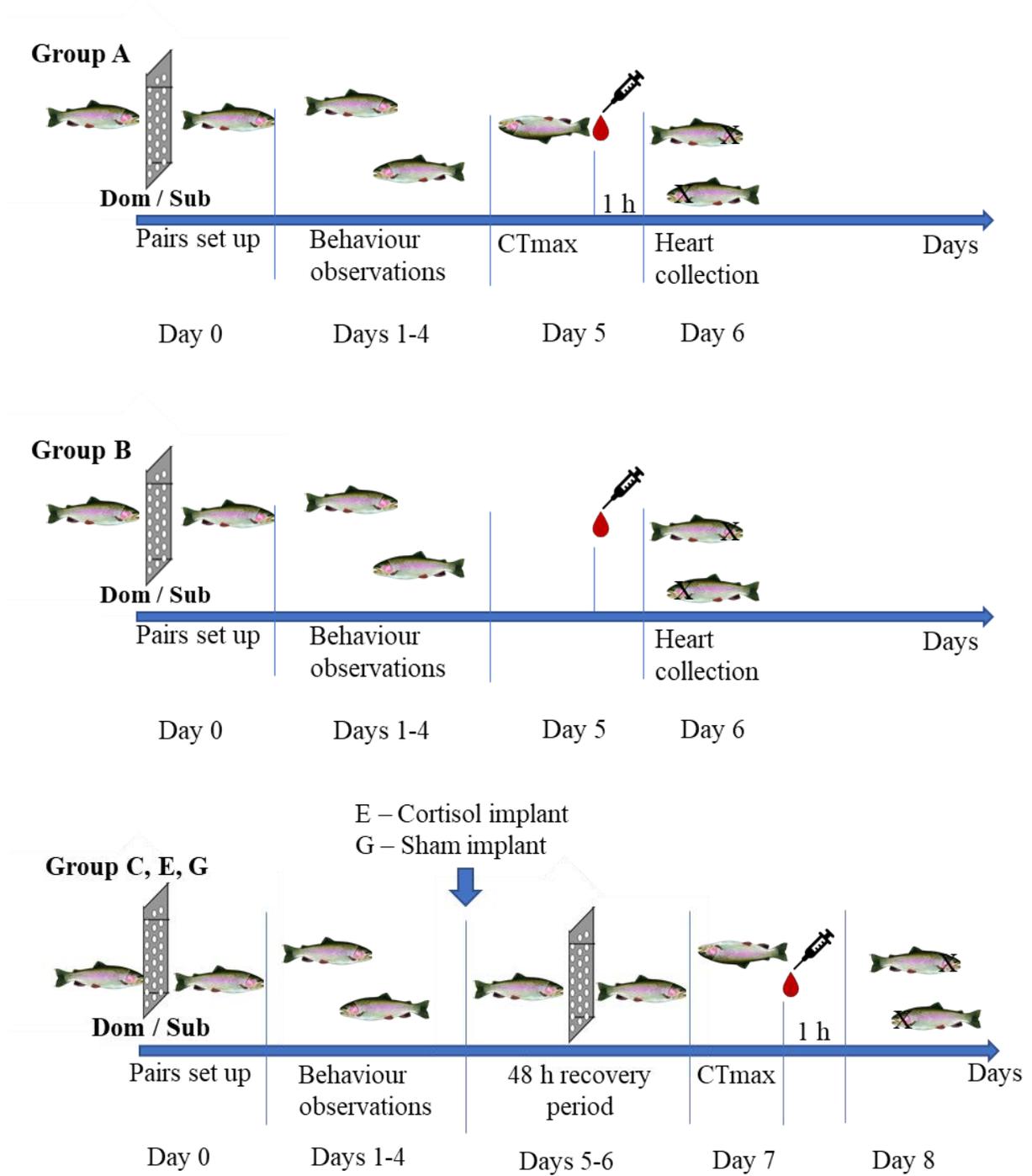
Transcript abundance of the gene of interest was normalized using β-actin and expressed relative to the value for dominant fish. Relative transcript abundances were compared using Student's *t*-tests.

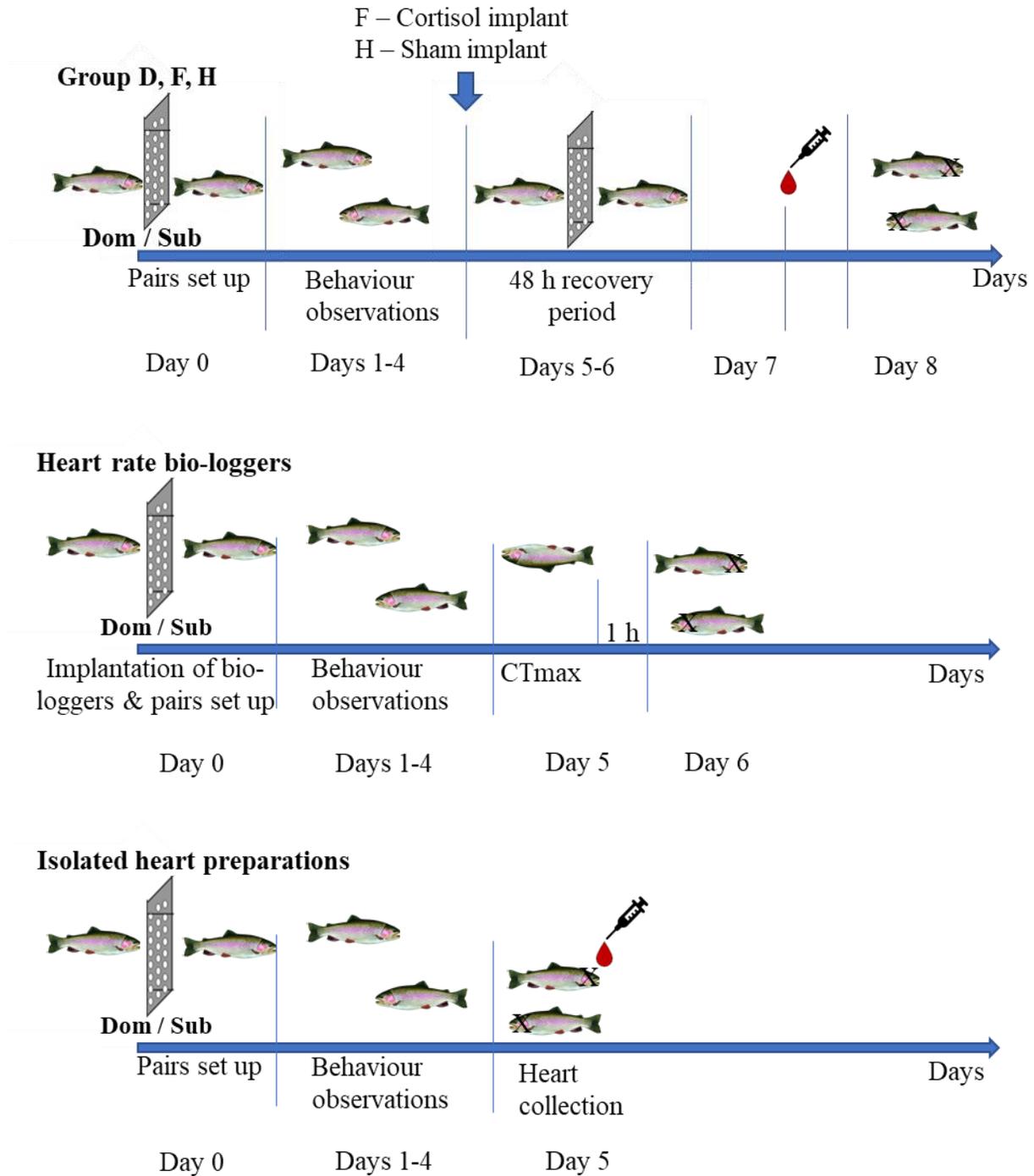
**Table 3.** Relative protein and mRNA abundances of collagen type I protein and genes involved in collagenous cardiac remodelling in the ventricle of subordinate and dominant rainbow trout (*Oncorhynchus mykiss*).

Protein or gene	Dominant	Subordinate	P-value
<b>Collagen type I</b>	1.00 ± 0.15 (6)	1.06 ± 0.17 (6)	0.80
<i>coll1a1</i>	1.32 ± 0.55 (5)	0.77 ± 0.29 (6)	0.41
<i>coll1a2</i>	1.51 ± 0.76 (5)	0.49 ± 0.06 (6)	0.25
<i>coll1a3</i>	1.58 ± 0.85 (5)	0.48 ± 0.07 (6)	0.27
<i>mmp2</i>	1.44 ± 0.68 (5)	0.92 ± 0.43 (6)	0.55
<i>mmp9</i>	1.85 ± 0.74 (5)	2.17 ± 0.80 (6)	0.78
<i>timp2</i>	1.10 ± 0.26 (4)	0.48 ± 0.27 (4)	0.15

*coll1a1*, collagen type I alpha 1; *coll1a2*, collagen type I alpha 2; *coll1a3*, collagen type 1 alpha 3; *mmp2*, matrix metalloproteinase 2; *mmp9*, matrix metalloproteinases 9; *timp2*, tissue inhibitor of metalloproteinases 2

Values are means ± SEM (*N*). Protein abundance was expressed relative to the value for the dominant fish. Transcript abundance of the gene of interest was normalized using β-actin and expressed relative to the value for dominant fish. Relative abundances were compared using Student's *t*-tests.





**Figure S1.** A schematic of experimental protocols (see text for details). Arrowheads indicate when implants were administered for Groups E through H. The syringe and red droplet represent withdrawal of a blood sample. *Dom*, dominant; *Sub*, subordinate

**Table S1.** Primers used for semi-quantitative real-time RT-PCR.

<b>Gene</b>	<b>Primer pair</b>	<b>GenBank accession number</b>	<b>Function or indicator</b>	<b>Efficiency; Amplicon size</b>	<b>Source</b>
<i><b><math>\beta</math>-actin</b></i>	F: AGAGCTACGAGCTGCCTGAC R: GTGTTGGCGTACAGGTCCTT	NM_001124235.1	Housekeeping gene	2; 179	Johansen et al. (2011)
<i><b>vmhc</b></i>	F: TGCTGATGCAATCAAAGGAA R: GGAACCTTGCCCAGATGGTT	AY009126.1	Cardiomyocyte hypertrophy	1.99; 191	Johansen et al. (2011)
<i><b>smlc2</b></i>	F: TCTCAGGCGGACAAGTTCA R: TAGCACAGGTTCTTGTAGTCC	NM001124678.1	Cardiomyocyte hypertrophy	2.01; 100	Johansen et al. (2011)
<i><b>mlp</b></i>	F: AGTTCGGGGACTCGGATAAG R: CGCCATCTTTCTCTGTCTGG	NM001124725.1 BC076439.1	Cardiomyocyte hypertrophy	1.95; 156	Johansen et al. (2011)
<i><b>rcan1</b></i>	F: AGTTTCCGGCGTGTGAGA R: GGGGACTGCCTATGAGGAC	BC076439.1*	Cardiomyocyte hypertrophy	1.92; 136	Johansen et al. (2011)
<i><b>mr</b></i>	F: GGCAGCGTTTGAGGAGATGA R: CATGGCGTCCAGTAGCTTGG	AF209873.1	Cortisol sensitivity	2; 127	Johansen et al. (2011)
<i><b>gr1</b></i>	F: TTCCAAGTCCACCACATCAA R: GGAGAGCTCCATCTGAGTCG	NM_001124730.1	Cortisol sensitivity	1.88; 115	Johansen et al. (2011)
<i><b>gr2</b></i>	F: GGGGTGATCAAACAGGAGAA R: CTCACCCACAGATGGAGAT	NM_001124482.1	Cortisol sensitivity	1.95; 140	Johansen et al. (2011)
<i><b>colla1</b></i>	F: GCTTTTGGCAAGAGGACAAG	NM001124177.1	Fibrosis	1.97; 154	Keen et al. (2015)

---

	R: GCAGATAACTTCGTTCGCACA				
<b><i>colla2</i></b>	F: GGCTGATCGGCTCTGTACTC R: TGGCTCTGCTGGTATCACTG	NM001124207.1	Fibrosis	1.96; 290	Keen et al. (2015)
<b><i>colla3</i></b>	F: CCCTGCTTTTTATGGTTGGA R: GCAGGGTTCTGGTTTCCATA	NM001124206.1	Fibrosis	2.03; 235	Keen et al. (2015)
<b><i>mmp2</i></b>	F: TGTATTGGGCAACATCAGGA R: CCCAGGAGACGATAGTCCAA	NM_198067.1*	Inhibits fibrosis	1.94; 219	Keen et al. (2015)
<b><i>mmp9</i></b>	F: GGTCCAGTTTTTCGTCATCGT R: AGACATGGGAGCCTCTCTGA	NM001124370.1	Inhibits fibrosis	1.99; 116	Keen et al. (2015)
<b><i>timp2</i></b>	F: CAGGCCATCCACCTACTGTT R: TGTTGCTCTCTTGCATACGG	NM_182874.1*	Inhibits MMPs	1.81; 113	Keen et al. (2015)

---

*vmhc*, ventricular myosin heavy chain; *smlc2*, slow myosin light chain 2; *mlp*, muscle LIM protein; *rca1*, regulator of calcineurin I; *mr*, mineralocorticoid receptor; *gr1*, glucocorticoid receptor 1; *gr2*, glucocorticoid receptor 2; *colla1*, collagen type I alpha 1; *colla2*, collagen type I alpha 2; *colla3*, collagen type I alpha 3; *mmp2*, matrix metalloproteinase 2; *mmp9*, matrix metalloproteinases 9; *timp2*, tissue inhibitor of metalloproteinases 2; \* indicates where GenBank sequences for zebrafish (*Danio rerio*) were used for primer design. The annealing temperature was 60°C for all primers.