Do aquatic ectotherms perform better under hypoxia after warm acclimation?

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Summary statement

Warm acclimation not only helps offset the detrimental effects of warming but could also improve performance under hypoxia. Therefore, acclimation is important in maintaining performance in a warmer, hypoxic world.

Glossary

Aerobic scope - The difference between MMR and SMR. Can be measured as absolute aerobic scope (AAS = MMR - SMR) or factorial aerobic scope (FAS = MMR/SMR).

Hypoxic performance - Any physiological metric/indicator of an individual's capacity to deal with hypoxia, e.g. metabolic performance (P_c, R) or tolerance (LOE, survival).

Loss of equilibrium - The inability of an organism to maintain an upright position within the water column. The PO_2 at LOE and/or time to LOE is used as a measure of hypoxia tolerance in fish.

Maximum metabolic rate - The maximal oxygen consumption of an organism.

P_c - Critical partial pressure of oxygen/critical oxygen tension. The PO_2 below which SMR can no longer be sustained and individuals typically resort to anaerobiosis and metabolic suppression.

P_{cmax} - Critical partial pressure of oxygen below which MMR can no longer be sustained.

Standard metabolic rate - The oxygen consumption of a post-absorptive organism where activity is reduced as much as possible.

Regulation index - The area encompassed by an individual's MO_2–PO_2 curve and derived oxyconformity line as a proportion of the area encompassed by this oxyconformity line and a hypothetical 'perfect' oxyregulatory response i.e. where the individual shows no change in SMR over a range of oxygen tensions.

Regulation values - The entire area under the MO_2–PO_2 curve as a proportion of the hypothetical response of an individual that shows no change in SMR over a range of oxygen tensions.

Acclimation temperature - Temperature where individuals are incubated for an extended period prior to experimentation.

Test temperature - The acute test temperature at which responses are measured.

Abstract

Aquatic animals increasingly encounter environmental hypoxia due to climate-related warming and/or eutrophication. Although acute warming typically reduces performance under hypoxia, the ability of organisms to modulate hypoxic performance *via* thermal acclimation is less understood. Here, we review the literature and ask whether hypoxic performance of aquatic ectotherms improves following warm acclimation. Interpretation of thermal acclimation effects is limited by reliance on data from experiments that are not designed to directly test for beneficial or detrimental effects on hypoxic performance. Most studies have tested hypoxic responses exclusively at test temperatures matching organisms' acclimation temperatures, precluding the possibility of distinguishing between acclimation and acute thermal effects. Only a few studies have applied appropriate methodology to identify beneficial thermal acclimation effects on hypoxic performance, i.e. acclimation to different temperatures prior to determining hypoxic responses at standardised test temperatures. These studies reveal that acute warming predominantly impairs hypoxic performance, whereas warm acclimation tends to be either beneficial or have no effect. If this generalises, we predict that warm-acclimated individuals in some species should outperform non-acclimated individuals under hypoxia. However, acclimation seems to only partially offset acute warming effects; therefore, aquatic ectotherms will likely display overall reduced hypoxic performance in the long term. Drawing on the appropriate methodology, future studies can quantify the ability of organisms to modulate hypoxic performance *via* (reversible) thermal acclimation and unravel the underlying mechanisms. Testing whether developmental acclimation and multigenerational effects allow for a more complete compensation is essential to allow us to predict species' resilience to chronically warmer, hypoxic environments.

Keywords: dissolved oxygen, critical oxygen tension, thermal acclimation, OCLTT, climate change, metabolic rate

Introduction

Oxygen is essential to almost all animal life to support aerobic metabolism and meet the energetic costs of living (Semenza, 2007; Willmer et al., 2004). That said, many aquatic organisms are physiologically capable of inhabiting environments that naturally undergo variation in dissolved oxygen levels, such as diurnally hypoxic tidal pools and eutrophic ponds, and seasonally hypoxic estuaries and fjords; some species even make a living in the almost permanently hypoxic areas of the deep sea (Childress and Seibel, 1998; Harrison et al., 2018; Jenny et al., 2016; Levin et al., 2009; Spicer, 2014).

Despite natural fluctuations in dissolved oxygen levels, all aquatic systems, from shallow freshwater environments to the deep ocean, are affected by the increasing frequency of hypoxic events and prevalence of prolonged, more severe hypoxia (Breitburg et al., 2018; Diaz and Rosenberg, 2008; Jenny et al., 2016) – phenomena that can drive reductions in biodiversity (Diaz and Rosenberg, 2008). Key factors driving the increase in hypoxia in freshwater and coastal environments include not only anthropogenic nutrient input but also climate change (Laffoley and Baxter, 2019). Global warming could drive a general reduction in oxygen levels across aquatic ecosystems through a combination of enhanced stratification, disrupted oxygen circulation by current systems, reduced oxygen solubility and enhanced rates of biological oxygen consumption (Altieri and Gedan, 2015; Breitburg et al., 2018; Rabalais et al., 2009). In marine systems, elevated water temperatures over the past 50 years have already driven a ~2 % decline in ocean oxygen levels (Schmidtko et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) predicts a future temperature rise of ~2 °C by 2100 (Pörtner et al., 2015), which may contribute to further predicted average decline in oceanic oxygen of up to ~7 % (Keeling et al., 2010). Although these changes may seem modest, any temperature-driven decline in average oxygen levels may exacerbate hypoxic episodes within ecosystems that already experience variability in oxygen levels (Breitburg et al., 2018; Rabalais et al., 2014).

The effects of temperature and low oxygen, singly and in combination, on the physiological performance of aquatic life have received considerable attention (Ern, 2019; Fry, 1971; Grieshaber et al., 1994; Hoefnagel and Verberk, 2015; Pörtner et al., 2017; Precht et al., 1973; Seibel and Deutsch, 2020). However, most studies of their interactive effects are relatively short term (McBryan et al., 2013). In experimental work, acute warming [i.e. increased test temperature (T_t; see Glossary)] typically drives reductions in hypoxic performance (see Glossary) in fish and invertebrates, including reduced survival time and lower capacity to maintain aerobic metabolism (raised P_c; see Glossary) (Herreid, 1980; McBryan et al., 2013). Whether acclimation to warming could modify the physiological responses to hypoxia in a 'beneficial' manner is less well understood (Gunderson et al., 2016; Huey and Berrigan, 1996; McBryan et al., 2016). Yet understanding these longer-term stressor interactions will be key to predicting how life will respond to an increasingly warm, oxygen-depleted aquatic environment.

It has long been recognised that prolonged exposure to elevated temperatures may result in thermal acclimation, i.e. physiological changes that alter the way organisms respond to temperature (Prosser, 1973). Thermal acclimation has been studied extensively under normoxic conditions by both thermal and evolutionary biologists, and these studies have demonstrated that acclimation needs to be considered when assessing the consequences of environmental warming (Angiletta, 2009; Precht et al., 1973; Prosser, 1973; Schulte et al., 2011; Seebacher et al., 2015; Somero, 2010). It is also essential to understand what role thermal acclimation will play in determining hypoxic performance in a warming world (McBryan et al., 2013). Broadly, effects of thermal acclimation on hypoxic performance could arise through shared physiological mechanisms that underpin responses to warming and hypoxia. This makes metabolism, or effects on oxygen supply and demand or anaerobic capacity, a promising avenue to explore (Fry, 1971; Harrison et al., 2018; Herreid, 1980; Kielland et al., 2019; McBryan et al., 2013; Pörtner, 2010; Seibel and Deutsch, 2020; Spicer, 2014).

147 Therefore, in this Review we ask whether warm acclimation is beneficial for hypoxic
148 performance in aquatic ectotherms. We first explain the methodological framework to
149 test for beneficial acclimation, before comparing hypoxic performance at ambient
150 and warm temperatures between (warm-) acclimated and non-acclimated individuals.
151 We use this overview of the literature to answer our question and highlight directions
152 for future research.

153

154 **Testing for beneficial effects of thermal acclimation on hypoxic performance**

155 Beneficial (or detrimental) acclimation can be identified by comparing the
156 physiological responses between individuals incubated at different temperatures
157 (acclimation temperature, T_a; see Glossary) for a given period at standardised acute
158 T_t using a well-established methodological framework (Huey and Berrigan, 1996;
159 Huey et al., 1999; Precht et al., 1973; Prosser, 1973). If thermal acclimation takes
160 place, the thermal sensitivity of a given physiological process is altered (i.e. T_a
161 modifies the effect of T_t on a physiological response) (Angiletta, 2009; Precht et al.,
162 1973; Prosser, 1973; Schulte et al., 2011). T_a can either increase, have no effect or
163 compensate (partially, fully or over) T_t effects on a physiological trait (Fig. 1A), but T_a
164 effects may not be uniform across the thermal range due to interactions between T_a
165 and T_t (Cossins and Bowler, 1987; Precht et al., 1973).

166

167 In the context of hypoxic responses, identifying beneficial effects of warm acclimation
168 would involve exposure of individuals to multiple T_a before hypoxic responses are
169 then assayed at one or more standardised T_t (Fig. 1B). We refer to those individuals
170 exposed to increased T_a as '(warm) acclimated' (Fig. 1C, red line) with the caveat
171 that, for some species, being kept at increased T_a does not necessarily guarantee
172 acclimation to that T_a (Fig. 1A, 'none'). We compare responses of 'acclimated'
173 individuals against those that have not been exposed to increased T_a. The latter are
174 referred to as 'non-acclimated' for brevity (Fig. 1C, blue line), but may represent the
175 control group or those individuals kept at lower T_a. Due to a paucity of data on
176 responses to chronic hypoxia, when referring to 'acclimation' throughout the Review,
177 we refer only to temperature and not hypoxic acclimation. We discuss only the

178 consequences of thermal acclimation for measures of physiological performance
179 made under short-term hypoxic exposure, concentrating on oxyregulation of aerobic
180 metabolism [specifically P_c of standard metabolic rate (SMR; see Glossary) and
181 regulation values (*R*; see Glossary)] and hypoxia tolerance [such as loss of
182 equilibrium (LOE; see Glossary) or survival], for which there are sufficient data to
183 compare responses across the various combinations of hypoxia, acute warming and
184 (thermal) acclimation.

185

186 Using this methodological framework (Fig. 1C), we begin by reviewing hypoxic
187 performance of non-acclimated individuals at ambient temperature (Fig. 1C, i).
188 Essentially, this group represents the responses to hypoxia in isolation. Next,
189 hypoxic performance of non-acclimated individuals exposed to acute warming is
190 examined (Fig. 1C, i versus ii). As temperature increases oxygen demand, and
191 hypoxia decreases oxygen supply, the general prediction is for poorer hypoxic
192 performance following an acute temperature increase (Fig. 1C, ii performs worse
193 than i). We then consider studies that investigate how acclimated individuals respond
194 to subsequent hypoxia. Testing for beneficial effects of thermal acclimation on
195 hypoxic performance requires comparison of responses of acclimated and non-
196 acclimated individuals at standardised T_t (Fig. 1C, i versus iii and/or ii versus iv).
197 However, most studies were not designed to address this aim and have measured
198 hypoxic responses solely at the respective temperature to which individuals have
199 been acclimated (Fig. 1C, i vs iv). We review these studies before critically analysing
200 other studies, which have directly identified beneficial/detrimental effects (Fig. 1C, if
201 acclimation is beneficial, iii should outperform i and/or iv should outperform ii). Finally,
202 having tested the predictions presented in Fig. 1C, we discuss the extent to which
203 hypoxic performance will be improved or impaired via acclimation in a chronically
204 warmer, more hypoxic environment.

205

206 **Hypoxic performance of non-acclimated individuals**

207 Hypoxic performance in non-acclimated individuals at ambient temperature

Numerous studies have investigated the responses to hypoxia in isolation (Fig. 1C, i), particularly the capacity of individuals to sustain SMR under (commonly acutely) declining environmental partial pressures of oxygen (PO_2) (Burnett and Stickle, 2001; Farrell and Richards, 2009; Grieshaber et al., 1994; Harrison et al., 2018; Herreid, 1980; Mangum and Van Winkle, 1973; McMahon, 2001; Spicer, 2016; Wu, 2002). In response to declining PO_2, SMR can display a spectrum of responses, with most responses typically falling between (1) oxyconformity, where SMR declines linearly with decreasing PO_2 and (2) oxyregulation, where SMR appears to remain independent of environmental PO_2, *via* alterations to ventilation and/or circulation, down to a critical PO_2 value (P_c) (Fig. 2A). Below P_c, individuals display oxyconformity and SMR declines with decreasing PO_2 (Grieshaber et al., 1994).

P_c is viewed as a key indicator of hypoxia tolerance because exposure to levels of 'severe' hypoxia below P_c results in time-limited survival (Boutilier and St-Pierre, 2000; Seibel, 2011). Below P_c, several mechanisms may become important in prolonging survival, including (1) anaerobic capacity/'anaerobic scope' (Sørensen et al., 2014), which involves the availability of energy reserves and the capacity of glycolytic enzymes to produce sufficient ATP, (2) metabolic suppression through reductions in energetically costly cellular processes such as protein synthesis and ion pumping to reduce ATP demand, and (3) the ability to deal with cellular damage and toxic anaerobic end products (Boutilier and St-Pierre, 2000; Mandic et al., 2009; Sørensen et al., 2014; Speers-Roesch et al., 2013). The interpretation of P_c and methodology used to define it is a continually evolving field (Reemeyer and Rees, 2019; Regan et al., 2019; Ultsch and Regan, 2019; Wood, 2018), and a recent meta-analysis offers a new interpretation of P_c as a corollary of aerobic scope (AS; see Glossary) rather than an indicator of tolerance *per se* (Seibel and Deutsch, 2020). It has long been recognised that maximum metabolic rate (MMR; see Glossary), like SMR, may also become limited by hypoxia, but at a higher oxygen tension (termed P_{cmax}; see Glossary) below which AS declines (Fry, 1971; Pörtner and Grieshaber, 1993) (Fig. 2A). However, the paucity of direct tests of the oxyregulation of MMR makes it difficult to quantify P_{cmax} and its thermal dependency in great detail; hence, whether oxygen limitation lowers AS at elevated temperatures is an area of ongoing debate (see Boxes 1 and 2).

Developments in the methodology to measure oxyregulatory capacity have occurred for species which display a degree of regulation but not a distinct P_c (Alexander and McMahon, 2004; Mueller and Seymour, 2011; Wood, 2018). For these types of species where the oxygen consumption rate (MO_2) responds gradually to declining PO_2 with no distinct breakpoint, an interesting question exists of whether the notion of SMR, as a level of MO_2 of no excess costs, truly exists. Models such as the 'regulation values (*R*)' (Alexander and McMahon, 2004) or 'regulation index (RI)' (Mueller and Seymour, 2011) have been developed to attempt to quantify oxyregulatory capacity. Both methods use a broadly similar approach: the oxyregulatory ability is expressed as the calculated area below the MO_2–PO_2 curve for an individual as a proportion of the area that would be observed for a perfect oxyregulatory response. However, there are differences between the two models. RI quantifies oxyregulatory capacity based upon the area encompassed by a perfect oxyregulatory response and oxyconformity line (Mueller and Seymour, 2011). *R* makes no assumption that oxyconformity represents the lowest limit of oxyregulatory capacity under declining PO_2 (Alexander and McMahon, 2004). Interestingly, the *R* model has explicitly extended the range of possible metabolic responses to hypoxia, going beyond oxyconformity and allowing the characterisation of 'hypoxia-sensitive' individuals. Such individuals display a large decrease in SMR at a comparatively small PO_2 reduction, a response that remains largely unexamined (Alexander and McMahon, 2004; Leiva et al., 2018) (Fig. 2B). These types of methods seem to be particularly suited to those aquatic invertebrate species that display curvilinear or sigmoidal relationships between SMR and PO_2 (Alexander and McMahon, 2004; Mangum and Van Winkle, 1973; Spicer and Morley, 2019; Sutcliffe, 1984). *R* or RI-type approaches have been criticised as they may not necessarily provide a clear threshold PO_2 (Regan et al., 2019), but this could make them more suitable for organisms that do not show a clear threshold (see above). In any case, both methods will overlap somewhat in that individuals with lower P_c will tend to have a greater area under the MO_2–PO_2 curve and thus greater oxyregulatory capacity (Regan et al., 2019).

Hypoxic performance in non-acclimated individuals exposed to warming

The responses of non-acclimated individuals to acute warming (Fig. 1C, i versus ii) are relatively well characterised, and typically include an increase in P_c (Dupont-Prinet et al., 2013; González-Ortegón et al., 2013; Herreid, 1980) and a reduction in survival time under low oxygen (Semsar-kazerouni et al., 2020; Vaquer-Sunyer and Duarte, 2011). Classic models attribute the increase in P_c to a rise in oxygen demand at higher temperatures, which shifts the point at which SMR can still be sustained (P_c) to a higher external PO_2 (Fry, 1971; Herreid, 1980). This increase in P_c can be offset somewhat by temperature driving concomitant increases in oxygen supply capacity, resulting in stronger increases in SMR relative to P_c (Fig. 3, Kielland et al., 2019; Seibel and Deutsch, 2020; Verberk et al., 2011). Several more recent models such as the 'oxygen- and capacity-limited thermal tolerance' (OCLTT) hypothesis (Pörtner, 2010; Pörtner et al., 2017), 'oxygen- and temperature-limited metabolic niche framework' (Ern, 2019), and Seibel and Deutsch's model of oxygen-supply capacity (Seibel and Deutsch, 2020) have expanded on these classic models, integrating other important metabolic traits such as MMR, P_{cmax} and AS (see Boxes 1 and 2). Here we focus on P_c of SMR, because this is what the majority of acclimation studies have measured. Irrespective of the precise model that predicts raised P_c of SMR, not allowing for acclimation, aquatic organisms will likely perform worse under warming and hypoxia (Deutsch et al., 2020; Verberk et al., 2016a; Verberk et al., 2016b).

Hypoxic performance of acclimated individuals

Warm acclimation could be predicted to affect hypoxic responses such as P_c by reducing the thermal sensitivity of oxygen demand (Seebacher et al., 2015) or increasing the capacity for oxygen supply (Sollid et al., 2005). Enhanced capacity for extracting and delivering oxygen could potentially be achieved by a number of mechanisms, such as increased respiratory surface area, ventilation rates or circulation rates or changes to the affinity for oxygen of respiratory pigments (Anttila et al., 2015; Hilton et al., 2008; McBryan et al., 2013; Sollid et al., 2005). Additionally, warm acclimation could be predicted to affect hypoxia tolerance by modulating anaerobic capacity, such as anaerobic enzyme activity and/or the ability to deal with

toxic anaerobic end products (Matthews and McMahon, 1999; Seebacher et al., 2015).

However, most thermal acclimation–hypoxia studies conducted to date were not designed to explicitly address whether thermal acclimation is beneficial for hypoxic performance. Hypoxic responses have primarily been measured 'at different acclimation temperatures', i.e. responses are only measured at the respective temperature to which individuals have been acclimated ($T_a = T_t$, Fig. 1C, i versus iv). Essentially, these types of study capture the outcome of a $T_a \times T_t$ interaction without an indication of the relative contributions of T_a or T_t, which would be required to explicitly test for beneficial or detrimental changes to performance (Havird et al., 2020). As these investigations make up the majority of acclimation–hypoxia studies, here, we assess the degree to which they can inform whether acclimation is beneficial (Fig. 1C, i versus iv). We then consider those few studies where hypoxic responses have been directly compared between acclimated and non-acclimated individuals at standardised T_t (Fig. 1C, i versus iii and/or ii versus iv).

Hypoxic performance at different acclimation temperatures

A number of studies, primarily involving fish and crustaceans, have investigated acute hypoxic performance following chronic incubation (weeks to months) at different acclimation temperatures (T_a) (Fig.1C, i versus iv). These longer term studies are often carried out in the pursuit of greater ecological realism, e.g. investigating temperature differences that may occur in nature (Al-Wassia and Taylor, 1977; Barnes et al., 2011; Butler and Taylor, 1975; Collins et al., 2013; Schurmann and Steffensen, 1997). When testing hypoxic responses solely at the temperature to which individuals are acclimated ($T_a = T_t$), the majority of studies have identified raised P_c associated with long-term incubation at a warm T_a (Al-Wassia and Taylor, 1977; Barnes et al., 2011; Butler and Taylor, 1975; Collins et al., 2013; Schurmann and Steffensen, 1997; Rogers et al., 2016; Kielland et al., 2019). However, in a smaller number of species, there is potential for long-term warming and associated effects on oxygen supply and demand to lead to P_c reaching a plateau. In such

cases, P_c does not increase with increased T_a, but either remains stable (Fry and Hart, 1948; Sollid et al., 2005; Yamanaka et al., 2013) or decreases (Ultsch et al., 1978). This suggests that enhancements in oxygen-supply capacity following warm acclimation compensate for the increased oxygen demand at higher temperatures. In conclusion, these studies demonstrate that a complete recovery of hypoxic performance can occur when individuals are exposed to chronic warming, but only rarely.

Tests of beneficial acclimation reveal warm acclimation improves hypoxic performance in some species

Few studies follow the classic methodology (Huey et al., 1999; Precht et al., 1973; Prosser, 1973) of determining hypoxic responses at standardised T_t post-acclimation (Fig. 1C, i versus iii and/or ii versus iv), which would allow the direct elucidation of acclimation effects on hypoxia thresholds. To our knowledge, these studies are restricted to those in Table 1, and, in general, T_t and T_a appear to differ in their effect on metabolic performance and hypoxia tolerance. This further corroborates the supposition that effects of thermal acclimation need to be taken into account when assessing how species will perform in warmer, hypoxic waters.

The effect of thermal acclimation on oxyregulation varies across species. In the triplefin fish *Bellapiscis lesleyae*, warm-acclimated individuals outperform non-acclimated individuals at raised T_t, displaying a lower P_c (Hilton et al., 2008). The mechanism governing this reduction in P_c was not determined but supply capacity is likely to be involved, as non-acclimated and acclimated individuals do not differ in SMR. However, warm acclimation has no effect on P_c in the sister species *Bellapiscis medius* (Hilton et al., 2008) nor in *Centropristis striata* (Slesinger et al., 2019) or two tropical fish species, where increased T_t increases P_c irrespective of T_a (Nilsson et al., 2010; Slesinger et al., 2019). Notably, if the study on one of these two tropical fish species, *A. doederleini* (Nilsson et al., 2010), had only measured P_c at T_a = T_t, the results could have implied that individuals perform worse at warm T_a (Fig. 4A). However, this study made the comparison between acclimated and non-

acclimated individuals, demonstrating that raised P_c was entirely attributable to T_t whereas T_a had no significant effect (Fig. 4B).

In molluscs, there is less evidence for improvements of metabolic performance in acclimated individuals, based upon regulation values, with no reported beneficial effects of T_a (Alexander and McMahon, 2004; Hicks and McMahon, 2002). Warm T_a reduces oxyregulatory capacity (regulation values) across all T_t in the zebra mussel *Dreissena polymorpha,* a response that may be detrimental in a chronically warming aquatic environment undergoing hypoxia (Alexander and McMahon, 2004). However, the authors suggested that a better oxyregulatory capacity following cold acclimation could be beneficial with regards to the particular ecology of the species, in order to overwinter under ice sheets, where chronic cold and hypoxia co-occur (Alexander and McMahon, 2004). It would be interesting to test whether variation across species in how warm acclimation affects oxyregulation is related to acclimation effects on SMR. None of the fish species tested so far appear to have the capacity to reduce SMR via acclimation (Hilton et al., 2008; Nilsson et al., 2010; Slesinger et al., 2019), something that might reduce P_c.

In terms of hypoxia tolerance, there is evidence of beneficial effects of thermal acclimation for both fish and molluscs. Warm acclimation increases time to LOE in killifish (McBryan et al., 2016) and lowers the oxygen saturation at LOE in salmon (Anttila et al., 2015) compared to non-acclimated individuals. This phenomenon is associated with gill and cardiac remodelling in warm-acclimated killifish and salmon, respectively (Anttila et al., 2015; McBryan et al., 2016).

Hypoxia tolerance also improves with warm acclimation in the zebra mussel *Dreissena polymorpha* (Matthews and McMahon, 1999), and this perhaps provides the most convincing support for the adoption of a beneficial acclimation framework to understand acclimation effects on hypoxic responses. Zebra mussels were acclimated to three temperatures (T_a = 5, 15 and 25 ºC) and exposed to severe hypoxia at three acute test temperatures (T_t = 5, 15 and 25 ºC) in a fully factorial experimental design (Matthews and McMahon, 1999). This species experiences

these temperatures frequently under normoxic conditions and can survive up to 45 ºC. Survival time under hypoxia decreased with increasing temperature when individuals were tested at their acclimation temperature ($T_a = T_t$) (Fig. 4C). However, when comparing individuals acclimated to different T_a at a given T_t it was clear that warm acclimation was beneficial, leading to an increase in hypoxic survival time compared to that of cold-acclimated individuals (for example, when comparing T_a = 25 ºC against T_a = 5 ºC: warm-acclimated individuals survived 1.9 times longer at T_t = 15 ºC and 1.6 times longer at T_t = 25 ºC). No effect of acclimation on survival under hypoxia was observed at T_t = 5 ºC and this was attributed to potential re-acclimation of individuals to cold T_t given the long survival time of ~ 40 days (Fig. 4D). The underpinning mechanism is unclear but it was suggested that individuals from warm T_a have reduced energy demands that could be sustained with lower rates of anaerobic metabolism and lower concomitant production of harmful end products (Matthews and McMahon, 1999).

This study exemplifies how the effects of warm T_a could be misinterpreted as being detrimental when acclimation actually buffers against the detrimental effects of acute warming. The interaction between T_a and T_t in this species, where improvements in hypoxia tolerance were observed at some but not all T_t, may also have ecological significance. Organisms may not always experience hypoxia at the temperature to which they have been acclimated. The responses to hypoxia at any given time in nature may be a complex combination of current thermal conditions (T_t) and previous thermal history (T_a), which has rarely been taken into account.

Will thermal acclimation prevent reductions in hypoxic performance of aquatic ectotherms in a chronically warming world?

Due to the paucity of data and studies using appropriate experimental designs, it is currently not possible to draw definitive conclusions on the effects of thermal acclimation on physiological responses to hypoxia or the extent to which acclimation can compensate for effects of raised acute temperatures. The studies reviewed here support the idea that some fish species show beneficial effects of warm acclimation

on oxyregulatory capacity and hypoxia tolerance. However, no crustacean studies to date have used the appropriate methodological framework to explicitly test for beneficial/detrimental effects of thermal acclimation on hypoxic performance. For molluscs, there is weak evidence for beneficial acclimation of metabolic performance and mixed evidence for hypoxia tolerance (Table 1).

Improvements to hypoxia tolerance due to increased T_a (i.e. beneficial acclimation) may be mediated through changes to enhance oxygen uptake and circulation or to reduce the thermal sensitivity of oxygen demand; alternatively, beneficial acclimation may increase the capacity for anaerobic metabolism or act through other, as yet unknown, mechanisms. Which of the above mechanisms are important awaits empirical testing (Matthews and McMahon, 1999). Despite a relatively good understanding of the physiological and biochemical mechanisms of acclimation under normoxic conditions (Prosser, 1973; Seebacher et al., 2015), empirical evidence is still required to understand how these mechanisms subsequently affect performance under hypoxia when tested at standardised T_t post-acclimation. Such an understanding will aid prediction of whether warm acclimation will positively or negatively affect hypoxic performance for a given species.

It is clear that thermal acclimation can be beneficial for hypoxic performance in some species (Fig. 1C, iv outperforms ii), in contrast to the relatively consistent detrimental effects of acute warming (such as raised P_c and reduced tolerance) on non-acclimated individuals (Herreid, 1980; Vaquer-Sunyer and Duarte, 2011) (Fig. 1C, ii performs worse than i). The studies that have only investigated responses where $T_a = T_t$ (Fig. 1C, i versus iv) do not facilitate direct identification of beneficial acclimation, but highlight that P_c remains raised in many cases under chronic warming. Thus, reversible acclimation may only partially compensate for the detrimental effects of raised acute thermal conditions on hypoxic performance (Fig. 1C, iv still performs worse than i), mirroring normoxic conditions, where physiological rates are also typically only partially compensated by acclimation (Seebacher et al., 2015).

Future directions

More studies applying the beneficial acclimation framework to hypoxic responses are needed. Studies where $T_a = T_t$ should use the term 'acclimation temperature' with caution, as the effects of acclimation cannot be distinguished without non-acclimated individuals for comparison (Havird et al., 2020). We suggest that studies applying this type of design instead refer only to 'measurement temperature'. From the few beneficial acclimation studies that are available so far, there appears to be considerable variation between species in their capacity to thermally acclimate their hypoxic performance, which may have significant fitness implications in determining so-called 'winners' and 'losers' (Somero, 2010). Future studies need to investigate a greater number of species in order to identify the sources of this variation, be it methodological (e.g. duration of acclimation, duration of P_c experiments), biological (e.g. mass effects on the speed and extent of acclimation, capacity to modulate oxygen supply via ventilation and circulation, oxygen demand, anaerobic capacity), or ecological (e.g. freshwater versus marine, temperature and oxygen levels experienced in the wild, latitude). In addition, future studies would preferably measure not only hypoxic performance but also putative mechanisms by which thermal acclimation can improve hypoxic performance (for example, does acclimation lower oxygen demand or increase the capacity for oxygen supply or anaerobic metabolism?). Finally, in this Review, we have focussed on reversible acclimation, which shows partial compensation, whereas developmental acclimation and transgenerational effects could allow for a more complete compensation. Understanding the physiological diversity, the mechanisms and time scales involved is essential if we wish to be able to assess the vulnerability of aquatic life to both predicted expansions in hypoxic regions under future climate change (Breitburg et al., 2018) and the widespread deoxygenation that is predicted during the Anthropocene (Laffoley and Baxter, 2019).

Conclusions

There is a reasonably good understanding of the hypoxic responses of non-acclimated individuals at ambient temperature. In non-acclimated individuals, the effects of acute warming are fairly consistent, tending to raise P_c and reduce the

hypoxia tolerance of many organisms (Herreid, 1980). However, the effects of warm acclimation on performance under hypoxic conditions remain unclear due to a paucity of experimental work with an appropriate experimental design. From the limited evidence to date, acclimation to increased temperature may partially improve the hypoxic performance of some, but not all, species. Drawing on the appropriate methodology, future studies can quantify the ability of organisms to modulate hypoxic performance via (reversible) thermal acclimation and unravel the underlying mechanisms. Thermal acclimation needs to be considered if we ever hope to accurately predict species' performance in a warmer, hypoxic world.

References

Al-Wassia, A. and Taylor, E. W. (1977). Some responses of the shore crab, *Carcinus maenas* (L.) to progressive hypoxia at different acclimation temperatures and salinities. *J. Comp. Physiol.* **122**, 391–402.

Alexander, J. E. and McMahon, R. F. (2004). Respiratory response to temperature and hypoxia in the zebra mussel *Dreissena polymorpha*. *Comp. Biochem. Physiol. - A Mol. Integr. Physiol.* **137**, 425–434.

Altieri, A. H. and Gedan, K. B. (2015). Climate change and dead zones. *Glob. Chang. Biol.* **21**, 1395–1406.

Angiletta, M. J. (2009). Thermal acclimation. In *Thermal Adaptation: A Theoretical and Empirical Synthesis*, pp. 126–155. Oxford University Press.

Anttila, K., Lewis, M., Prokkola, J. M., Kanerva, M., Seppanen, E., Kolari, I. and Nikinmaa, M. (2015). Warm acclimation and oxygen depletion induce species-specific responses in salmonids. *J. Exp. Biol.* **218**, 1471–1477.

Barnes, R., King, H. and Carter, C. G. (2011). Hypoxia tolerance and oxygen regulation in Atlantic salmon, *Salmo salar* from a Tasmanian population. *Aquaculture* **318**, 397–401.

Boutilier, R. G. and St-Pierre, J. (2000). Surviving hypoxia without really dying. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* **126**, 481–490.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., et al. (2018). Declining oxygen in the global ocean and coastal waters. *Science* **359**, eaam7240.

Burnett, L. E. and Stickle, W. B. (2001). Physiological responses to hypoxia. In *Coastal Hypoxia: Consequences for Living Resources and Ecosystems* (ed. Rabalais, N. N. and Turner, R. E.), pp. 101–114. Washington: American Geophysical Union.

Butler, P. J. and Taylor, E. W. (1975). The effect of progressive hypoxia on respiration in the dogfish (*Scyliorhinus canicula*) at different seasonal temperatures. *J. Exp. Biol.* **63**, 117–130.

Childress, J. J. and Seibel, B. A. (1998). Life at stable low oxygen levels: adaptations of animals to oceanic oxygen minimum layers. *J. Exp. Biol.* **201**, 1223–1232.

Collins, G. M., Clark, T. D., Rummer, J. L. and Carton, A. G. (2013). Hypoxia tolerance is conserved across genetically distinct sub-populations of an iconic, tropical Australian teleost (*Lates calcarifer*). *Conserv. Physiol.* **1**, cot029.

Cossins, A. R. and Bowler, K. (1987). Rate compensations and capacity adaptations. In *Temperature Biology of Animals*, pp. 155–203. Springer.

Deutsch, C., Penn, J. L. and Seibel, B. (2020). Metabolic trait diversity shapes marine biogeography. *Nature* **585**, 557–562.

Diaz, R. J. and Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science* **321**, 926–929.

Dupont-Prinet, A., Pillet, M., Chabot, D., Hansen, T., Tremblay, R. and Audet, C. (2013). Northern shrimp (*Pandalus borealis*) oxygen consumption and metabolic enzyme activities are severely constrained by hypoxia in the Estuary and Gulf of St. Lawrence. *J. Exp. Mar. Bio. Ecol.* **448**, 298–307.

Ern, R. (2019). A mechanistic oxygen- and temperature-limited metabolic niche framework. *Phil. Trans. R. Soc. B* **374**, 20180540.

Farrell, A. P. and Richards, J. G. (2009). Defining hypoxia. In *Fish Physiology: Hypoxia* (ed. Farrell, A. P., Richards, J. G. and Brauner, C. J.), pp. 487–503. Amsterdam: Academic Press.

Fry, F. E. J. (1971). The effect of environmental factors on the physiology of fish. In *Fish physiology*, pp. 1–98. Elsevier.

Fry, F. E. J. and Hart, J. S. (1948). The Relation of Temperature to Oxygen Consumption in the Goldfish. *Biol. Bull.* **94**, 66–77.

González-Ortegón, E., Pascual, E. and Drake, P. (2013). Respiratory responses to salinity, temperature and hypoxia of six caridean shrimps from different aquatic habitats. *J. Exp. Mar. Bio. Ecol.* **445**, 108–115.

Grieshaber, M. K., Hardewig, I., Kreutzer, U. and Pörtner, H. O. (1994). Physiological and metabolic responses to hypoxia in invertebrates. *Rev. Physiol. Biochem. Pharmacol.* **125**, 43–147.

Gunderson, A. R., Armstrong, E. J. and Stillman, J. H. (2016). Multiple stressors in a changing world: the need for an improved perspective on physiological responses to the dynamic marine environment. *Ann. Rev. Mar. Sci.* **8**, 357–378.

Harrison, J. F., Greenlee, K. J. and Verberk, W. C. E. P. (2018). Functional hypoxia in insects: definition, assessment, and consequences for physiology, ecology, and evolution. *Annu. Rev. Entomol.* **63**, 303–325.

Havird, J. C., Neuwald, J. L., Shah, A. A., Mauro, A., Marshall, C. A. and Ghalambor, C. K. (2020). Distinguishing between active plasticity due to thermal acclimation and passive plasticity due to Q10 effects: why methodology matters. *Funct. Ecol.* **00**, 1–14.

Herreid, C. F. (1980). Hypoxia in invertebrates. *Comp. Biochem. Physiol. Part A Physiol.* **67**, 311–320.

Hicks, D. W. and McMahon, R. F. (2002). Respiratory responses to temperature and hypoxia in the nonindigenous brown mussel, Perna perna (Bivalvia:Mytilidae), from the Gulf of Mexico. *J. Exp. Mar. Bio. Ecol.* **277**, 61–78.

Hilton, Z., Wellenreuther, M. and Clements, K. D. (2008). Physiology underpins habitat partitioning in a sympatric sister-species pair of intertidal fishes. *Funct. Ecol.* **22**, 1108–1117.

Hoefnagel, K. N. and Verberk, W. C. E. P. (2015). Is the temperature-size rule mediated by oxygen in aquatic ectotherms? *J. Therm. Biol.* **54**, 56–65.

Huey, R. B. and Berrigan, D. (1996). Testing evolutionary hypotheses of acclimation. In *Animals and Temperature: Phenotypic and Evolutionary Adaptation* (ed. Johnston, I.A. and Bennett, A. F.), pp. 205–237. Cambridge University Press.

Huey, R. B., Berrigan, D., Gilchrist, G. W. and Herron, J. C. (1999). Testing the adaptive significance of acclimation: a strong inference approach. *Am. Zool.* **39**,

323–336.

Jenny, J. P., Francus, P., Normandeau, A., Lapointe, F., Perga, M. E., Ojala, A., Schimmelmann, A. and Zolitschka, B. (2016). Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. *Glob. Chang. Biol.* **22**, 1481–1489.

Keeling, R. E., Körtzinger, A. and Gruber, N. (2010). Ocean deoxygenation in a warming world. *Ann. Rev. Mar. Sci.* **2**, 199–229.

Kielland, Ø. N., Bech, C. and Einum, S. (2019). Warm and out of breath: Thermal phenotypic plasticity in oxygen supply. *Funct. Ecol.* **33**, 2142–2149.

Laffoley, D. and Baxter, J. M. (2019). *Ocean deoxygenation: everyone's problem - causes, impacts, consequences and solutions*. Gland, Switzerland: IUCN.

Leiva, F. P., Garcés, C., Verberk, W. C. E. P., Care, M., Paschke, K. and Gebauer, P. (2018). Differences in the respiratory response to temperature and hypoxia across four life-stages of the intertidal porcelain crab Petrolisthes laevigatus. *Mar. Biol.* **165**, 146.

Levin, L. A., Ekau, W., Gooday, A. J., Jorissen, F., Middelburg, J. J., Naqvi, S. W. A., Neira, C., Rabalais, N. N. and Zhang, J. (2009). Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences* **6**, 2063–2098.

Mandic, M., Todgham, A. E. and Richards, J. G. (2009). Mechanisms and evolution of hypoxia tolerance in fish. *Proc. R. Soc. B Biol. Sci.* **276**, 735–744.

Mangum, C. and Van Winkle, W. (1973). Responses of aquatic invertebrates to declining oxygen conditions. *Am. Zool.* **13**, 529–541.

Matthews, M. A. and McMahon, R. F. (1999). Effects of temperature and temperature acclimation on survival of zebra mussels (*Dreissena polymorpha*) and Asian clams (*Corbicula fluminea*) under extreme hypoxia. *J. Molluscan Stud.* **65**, 317–325.

McBryan, T. L., Anttila, K., Healy, T. M. and Schulte, P. M. (2013). Responses to temperature and hypoxia as interacting stressors in fish: implications for adaptation to environmental change. *Integr. Comp. Biol.* **53**, 648–659.

McBryan, T. L., Healy, T. M., Haakons, K. L. and Schulte, P. M. (2016). Warm acclimation improves hypoxia tolerance in *Fundulus heteroclitus*. *J. Exp. Biol.* **219**, 474–484.

McMahon, B. R. (2001). Respiratory and circulatory compensation to hypoxia in crustaceans. *Respir. Physiol.* **128**, 349–364.

Mueller, C. A. and Seymour, R. S. (2011). The regulation index: a new method for assessing the relationship between oxygen consumption and environmental oxygen. *Physiol. Biochem. Zool.* **84**, 522–532.

Nilsson, G. E., Östlund-Nilsson, S. and Munday, P. L. (2010). Effects of elevated temperature on coral reef fishes: loss of hypoxia tolerance and inability to acclimate. *Comp. Biochem. Physiol. - A Mol. Integr. Physiol.* **156**, 389–393.

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. and Grieshaber, M. K. (1993). Critical PO2(s) in oxyconforming and oxyregulating animals: Gas exchange, metabolic rate and the mode of energy production. In *The vertebrate gas transport cascade: adaptations to environment and mode of life* (ed. Bicudo, J.), pp. 330–357. Boca Raton: CRC.

Pörtner, H. O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., Schmidt, D. N. and Zavialov, P. O. (2015). Ocean systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L. L.), pp. 411–484. Cambridge: Cambridge University Press.

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.

Precht, H., Christophersen, J., Hensel, H. and Larcher, W. (1973). *Temperature and Life*. 2nd ed. Berlin: Springer-Verlag.

Prosser, C. L. (1973). *Comparative Animal Physiology.* Philadelphia: W.B. Saunders.

Rabalais, N. N., Turner, R. E., Díaz, R. J. and Justić, D. (2009). Global change and eutrophication of coastal waters. *ICES J. Mar. Sci.* **66**, 1528–1537.

Rabalais, N. N., Cai, W. J., Carstensen, J., Conley, D. J., Fry, B., Hu, X., Quiñones-Rivera, Z., Rosenberg, R., Slomp, C. P., Turner, R. E., et al. (2014). Eutrophication-driven deoxygenation in the coastal ocean. *Oceanography* **27**, 172–183.

Reemeyer, J. E. and Rees, B. B. (2019). Standardizing the determination and interpretation of Pcrit in fishes. *J. Exp. Biol.* **222**, jeb210633.

Regan, M. D., Mandic, M., Dhillon, R. S., Lau, G. Y., Farrell, A. P., Schulte, P. M., Seibel, B. A., Speers-Roesch, B., Ultsch, G. R. and Richards, J. G. (2019). Don't throw the fish out with the respirometry water. *J. Exp. Biol.* **222**, jeb200253.

Rogers, N. J., Urbina, M. A., Reardon, E. E., Mckenzie, D. J. and Wilson, R. W. (2016). A new analysis of hypoxia tolerance in fishes using a database of critical oxygen level (P_{crit}). *Conserv. Physiol.* **4**, cow012.

Schmidtko, S., Stramma, L. and Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. *Nature* **542**, 335–339.

Schulte, P. M., Healy, T. M. and Fangue, N. A. (2011). Thermal performance curves, phenotypic plasticity, and the time scales of temperature exposure. *Integr. Comp. Biol.* **51**, 691–702.

Schurmann, H. and Steffensen, J. F. (1997). Effects of temperature, hypoxia and activity on the growth and metabolism of juvenile Atlantic cod. *J. Fish Biol.* **50**, 1166–1180.

Seebacher, F., White, C. R. and Franklin, C. E. (2015). Physiological plasticity increases resilience of ectothermic animals to climate change. *Nat. Clim. Chang.* **5**, 61–66.

Seibel, B. A. (2011). Critical oxygen levels and metabolic suppression in oceanic oxygen minimum zones. *J. Exp. Biol.* **214**, 326–336.

Seibel, B. A. and Deutsch, C. (2020). Oxygen supply capacity in animals evolves to meet maximum demand at the current oxygen partial pressure regardless of size and temperature. *J. Exp. Biol.* **223**, jeb.210492.

Semenza, G. L. (2007). Life with oxygen. *Science* **318**, 62–64.

Semsar-kazerouni, M., Boerrigter, J. G. J. and Verberk, W. C. E. P. (2020). Changes in heat stress tolerance in a freshwater amphipod following starvation: The role of oxygen availability, metabolic rate, heat shock proteins and energy reserves. *Comp. Biochem. Physiol. -Part A Mol. Integr. Physiol.* **245**, 110697.

Slesinger, E., Andres, A., Young, R., Seibel, B., Saba, V., Phelan, B., Rosendale, J., Wieczorek, D. and Saba, G. (2019). The effect of ocean warming on black sea bass (Centropristis striata) aerobic scope and hypoxia tolerance. *PLoS One* **14**, 1–22.

Sollid, J., Weber, R. E. and Nilsson, G. E. (2005). Temperature alters the respiratory surface area of crucian carp *Carassius carassius* and goldfish *Carassius auratus*. *J. Exp. Biol.* **208**, 1109–1116.

Somero, G. N. (2010). The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine “winners” and “losers.” *J. Exp. Biol.* **213**, 912–920.

Sørensen, C., Munday, P. L. and Nilsson, G. E. (2014). Aerobic vs. anaerobic scope: Sibling species of fish indicate that temperature dependence of hypoxia tolerance can predict future survival. *Glob. Chang. Biol.* **20**, 724–729.

Speers-Roesch, B., Mandic, M., Groom, D. J. E. and Richards, J. G. (2013). Critical oxygen tensions as predictors of hypoxia tolerance and tissue metabolic responses during hypoxia exposure in fishes. *J. Exp. Mar. Bio. Ecol.* **449**, 239–249.

Spicer, J. I. (2014). What can an ecophysiological approach tell us about the physiological responses of marine invertebrates to hypoxia? *J. Exp. Biol.* **217**,

46–56.

Spicer, J. I. (2016). Respiratory responses of marine animals to environmental hypoxia. In *Stressors in the Marine Environment* (ed. Solan, M.) and Whiteley, N. M.), pp. 25–35. Oxford: Oxford University Press.

Spicer, J. I. and Morley, S. A. (2019). Will giant polar amphipods be first to fare badly in an oxygen-poor ocean? Testing hypotheses linking oxygen to body size. *Phil. Trans. R. Soc. B* **374**, 20190034.

Sutcliffe, D. W. (1984). Quantitative aspects of oxygen uptake by *Gammarus* (Crustacea, Amphipoda): a critical review. *Freshw. Biol.* **14**, 443–489.

Ultsch, G. R. and Regan, M. D. (2019). The utility and determination of P_{crit} in fishes. *J. Exp. Biol.* **222**, jeb203646.

Ultsch, G. R., Boschung, H. and Ross, M. J. (1978). Metabolism, critical oxygen tension, and habitat selection in darters (*Etheostoma*). *Ecology* **59**, 99–107.

Vaquer-Sunyer, R. and Duarte, C. M. (2011). Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Glob. Chang. Biol.* **17**, 1788–1797.

Verberk, W. C. E. P., Bilton, D. T., Calosi, P. and Spicer, J. I. (2011). Oxygen supply in aquatic ectotherms: partial pressure and solubility together explain biodiversity and size patterns. *Ecology* **92**, 1565–1572.

Verberk, W. C. E. P., Overgaard, J., Ern, R., Bayley, M., Wang, T., Boardman, L. and Terblanche, J. S. (2016a). Does oxygen limit thermal tolerance in arthropods? a critical review of current evidence. *Comp. Biochem. Physiol. Part A Mol. Integr. Physiol.* **192**, 64–78.

Verberk, W. C. E. P., Durance, I., Vaughan, I. P. and Ormerod, S. J. (2016b). Field and laboratory studies reveal interacting effects of stream oxygenation and warming on aquatic ectotherms. *Glob. Chang. Biol.* **22**, 1769–1778.

Willmer, P., Stone, G. and Johnston, I. (2004). *Environmental Physiology of Animals 2nd Edition*. John Wiley & Sons, Inc.

Wood, C. M. (2018). The fallacy of the P_{crit} – are there more useful alternatives? *J. Exp. Biol.* **221**, jeb163717.

Wu, R. S. S. (2002). Hypoxia: from molecular responses to ecosystem responses. *Mar. Pollut. Bull.* **45**, 35–45.

Yamanaka, H., Takahara, T., Kohmatsu, Y. and Yuma, M. (2013). Body size and temperature dependence of routine metabolic rate and critical oxygen concentration in larvae and juveniles of the round crucian carp *Carassius auratus grandoculis* Temminck & Schlegel 1846. *J. Appl. Ichthyol.* **29**, 891–895.

Figure legends

Fig. 1 Testing for beneficial effects of thermal acclimation on hypoxic performance. (A) Following an acute temperature increase (T_1 to T_2, dashed arrow) individuals may be able to acclimate a physiological response (e.g. P_c) but to differing degrees (Huey and Berrigan, 1996). Acclimation effects (indicated by solid arrows) may either increase ('inverse') or compensate ('partial', 'full' or 'overcompensated') the effects of the acute temperature increase. Individuals may also display no ability to acclimate a physiological response ('none'). (B) Acclimation can be tested using classic methodology, where individuals acclimated to different temperatures (T_a) have hypoxic responses measured at standardised test temperatures (T_t) (a 2x2 design is depicted for clarity but could include a range of different T_a or T_t). (C) A thermal reaction norm displaying the effects of T_t and T_a on a physiological response (e.g. P_c). This facilitates comparison of hypoxic performance between non-acclimated (blue) and acclimated individuals (red) at each T_t, either ambient or warm T_t. Note that this is a simplified diagram displaying a singular acclimation response (partial). A full thermal performance curve would vary markedly in its shape and slope depending upon the metric of performance and variation between individuals and species. T_a effects may not be uniform across T_t. Whatever effects are elicited, whether they are beneficial or detrimental can be interpreted by comparing effects between T_a at the T_t of interest.

Fig. 2 Measures of aerobic metabolic regulation in response to declining PO_2 (A) Critical oxygen tensions are the most commonly used metric of hypoxic performance. SMR can be sustained down to a critical oxygen tension, P_c, before a transition to anaerobic and/or hypometabolism occurs. MMR is less well maintained, and P_{cmax} occurs at much higher PO_2. AS represents the difference between MMR and SMR. Alpha represents the oxygen-supply capacity (Seibel and Deutsch, 2020, Box 2). (B) Regulation values have been proposed to characterise the degree of oxyregulation displayed by different species. Regulation values equal the proportion represented by the area under an MO_2–PO_2 curve, relative to the area displayed by a perfect oxyregulator. MO_2 is standardised against the highest MO_2 observed regardless of where it occurs across the PO_2 range between 0–100 % air saturation (% a.s.). Oxyregulators display values > 50 %, oxyconformity lies at 50 % and hypoxia-sensitive individuals display values < 50 % (Leiva et al., 2018).

Fig. 3 Temperature sensitivity of P_c. Increased T_t (red arrow) typically increases SMR and leads to an increase in P_c. The increase in P_c is offset by temperature-driven increases in oxygen-supply capacity and, as a result, the lines do not overlap and the ascending part becomes steeper (indicative of a higher oxygen-supply capacity) at higher temperatures (Kielland et al., 2019; Seibel and Deutsch, 2020). Colours indicate temperatures increasing from cold (blue) to warm (red).

Fig. 4 Effects of temperature acclimation (T_a) and acute test temperature (T_t) on hypoxic responses. (A,B) Individuals of the tropical fish *Apogon doederleini* were acclimated to either T_a = 29 °C or 32 °C for 7 days prior to determination of P_c under acutely declining oxygen tensions at T_t = 32 °C (mean ± SE) (data from Nilsson et al., 2010). (A) When $T_a = T_t$ it appears that warm acclimation temperatures are detrimental to P_c but this is not the case. (B) Using a classic methodological approach, the effects of T_a can be disentangled from those of T_t. Increased T_t is detrimental and raises P_c in non-acclimated individuals. Comparing responses within T_t = 32 °C between different T_a, warm acclimation was not detrimental and had no significant effect on P_c. (C,D) Hypoxia tolerance in the zebra mussel, *Dreissena polymorpha*. Individuals acclimated to T_a = 5, 15 and 25 °C were exposed to severe hypoxia (< 3 % a.s.) at T_t = 5, 15 and 25 °C in a fully factorial experiment and survival time was measured (mean ± SE) (C) When $T_a = T_t$, it appears that warm acclimation temperatures are detrimental to hypoxia tolerance. (D) Increased T_t is detrimental to hypoxic survival in individuals acclimated to the same T_a. Comparing responses within T_t between different T_a shows that warm acclimation is beneficial and significantly increases hypoxic survival time at T_t = 15 and 25 °C (1.9 and 1.6 fold increase in survival time, respectively) but has no significant effect at T_t = 5 °C (black arrows indicate direction of T_a and T_t effects) (data from Matthews and McMahon, 1999).

Table 1. Studies investigating beneficial acclimation of hypoxic performance

Species	Performance	T_a (ºC)	Standard T_t (ºC)	Warm T_t effect?	Warm T_a effect?	Interaction?	Response type (see Fig. 1A)	Reference
Fish								
Bellapiscis lesleyae	P_c	15,20	25	-	+	n.a.	Partial	Hilton et al., (2008)
Bellapiscis medius	P_c	15,20	25	-	No effect	n.a.	None	Hilton et al., (2008)
Fundulus heteroclitus	Time to LOE	15,20, 25,30	20,25,30	-	+	No	Partial	McBryan et al., (2016)
Pomacentrus moluccensis	P_c	29,32	32	-	No effect	n.a.	None	Nilsson et al., (2010)
Apogon (as *Ostorhinchus) doederleini*	P_c	29,32	32	-	No effect	n.a.	None	Nilsson et al., (2010)
Centropistis striata	P_c	22,30	30	-	No effect	n.a.	None	Slesinger et al., (2019)
Salmo salar	Critical PO_2 for LOE	7.7,14.9	12	n.a.	+	n.a	n.a.	*Anttila et al., (2015)

Salvelinus alpinus	Time to LOE	7.7,14.9	12	n.a.	No effect	n.a.	n.a.	*Anttila et al., (2015)
Mollusca								
Dreissena polymorpha	Survival time	5,15,25	5,15,25	-	+ at T_t = 15, 25 No effect at T_t = 5	Yes	Partial	Matthews and McMahon, (1999)
Dreissena polymorpha	Regulation values	5,15,25	5,15,25	+	-	No	Over-compensated	Alexander and McMahon, (2004)
Corbicula fluminea	Survival time	5,15,25	5, 25	-	No effect	No	None	Matthews and McMahon, (1999)
Perna perna	Regulation values	15,20,25	10,15,20, 25,30	+	No effect	No	None	Hicks and McMahon, (2002)

*focussing only upon prior thermal acclimation conducted under normoxic conditions before hypoxia tolerance was determined
n.a. = not applicable

Box 1. Beyond Pc of SMR – i. OCLTT (Pörtner, 2010) and metabolic niche framework (Ern, 2019)

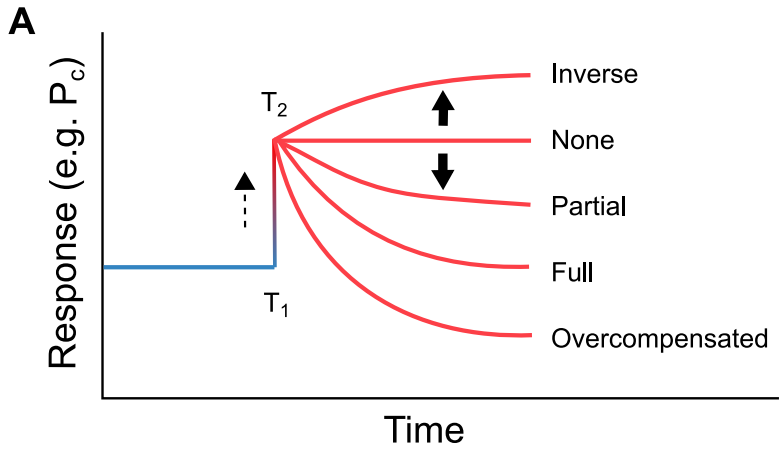
The OCLTT hypothesis (left panel) suggests an optimal thermal range (Topt) exists where aerobic performance (solid black line) is maximised. At both higher and lower temperatures aerobic performance declines; these temperatures are referred to as 'pejus' temperatures (Tp). Oxygen limitation is hypothesized to cause the decline in MMR and AS, which approaches zero at critical temperatures (Tc). Pc of SMR (dashed red line) is proposed to mirror the pattern for AS, being lowest at Topt and increasing at Tp. At Tc, Pc equals normoxia and individuals rely on anaerobic metabolism. Pcmax approximates normoxia across the thermal range. Few studies have focused on predictions from the OCLTT hypothesis at temperatures below Topt and there is little evidence for cold-induced oxygen limitation (Verberk et al., 2016a) or increasing Pc. With warming, there is support that Pc and AS vary in tandem along thermal clines, but Pc can increase while absolute aerobic scope (AAS) is increasing or constant, as accounted for by recent models (Ern, 2019; Seibel and Deutsch, 2020). Studies so far demonstrate that, except for eelpout (Pörtner and Knust, 2007), Pc tends not to reach normoxia at temperatures where individuals are alive (i.e. at a Tc < CTmax) (Seibel and Deutsch, 2020). Given the mixed evidence for OCLTT (Jutfelt et al., 2018; Pörtner et al., 2017; Verberk et al., 2016a), the 'oxygen- and temperature-limited metabolic framework' (Ern, 2019) has been proposed (right panel). Here, Pcrit = Tcrit (yellow

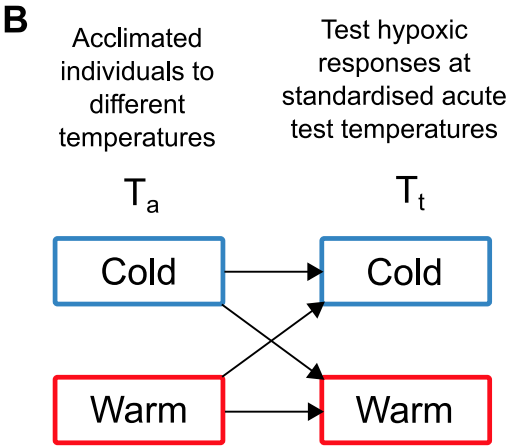
line) at equivalent temperature and PO_2. A zone of hypoxic insensitivity is assumed near normoxia above ~ 19 kPa (i.e. we assume Pcmax = ~19 kPa). At temperatures > Tcrit and PO2 < Pcrit, survival becomes dependent upon anaerobic capacity (AC, black arrows) until terminal temperature or PO_2 (T_{term} or P_{term}, red line). For oxygen-limited species: CTmax (grey line) = Tterm under normoxia, and thermal tolerance will decline with declining PO_2. With increasing temperatures, Pcrit and AAS (dotted isopleths) rise in tandem until preferred temperatures (Tpref, green line) after which Pcrit keeps increasing, while AAS declines. Pcrit approximates normoxia, where AAS = 0 at a temperature < Tterm. For non-oxygen limited species: CTmax < Tterm under normoxia and thermal tolerance does not decrease with hypoxia until PCTmax, the oxygen limit for thermal tolerance. Similar to oxygen-limited organisms, Pcrit rises with increased temperature and approximates normoxia where AAS = 0. However, Pcrit approaches normoxia and AAS = 0 at a temperature > CTmax. Thus, for non-oxygen limited species, Pcrit for an organism across its thermal range will never approximate normoxia. The framework also integrates behavioural responses by considering how PO2 may limit TPref, termed PTPref, and the possible causes of avoidance behaviour at sub-optimal temperature and PO_2 (Tavoid and Pavoid, blue line).

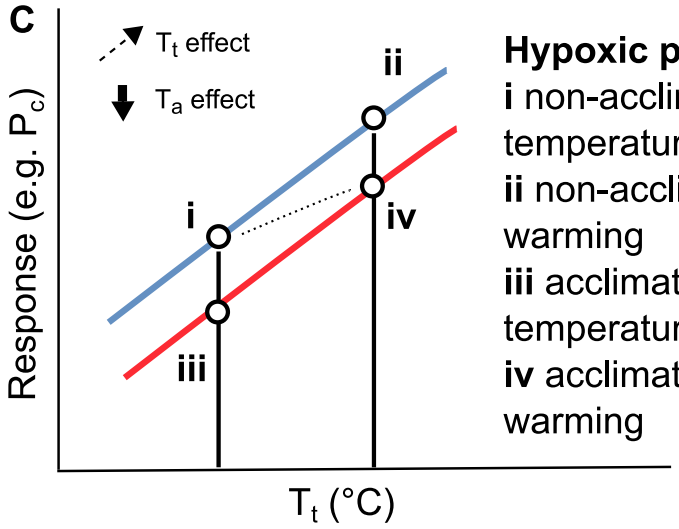
Box 2 - Beyond Pc of SMR – ii. Oxygen supply capacity model (Seibel and Deutsch, 2020)

Seibel and Deutsch (2020) propose a quantitative model based upon a meta-analysis of Pc, SMR and MMR, with a view that oxygen supply capacity has evolved to meet maximum demand. In their hypoxia model they propose a novel metric, the oxygen supply capacity (α) (Fig. 2A), which is the rate at which metabolic rate increases with PO_2 below a critical oxygen tension. At a given temperature, α is constant so that SMR/Pc = MMR/Pcmax. Pcmax is modelled to be ~ 21kPa for most species, except those that experience persistent hypoxia. From this, it follows that MMR should decline proportionally with PO_2 by 4.7% kPa^{-1} for normoxic species. Furthermore, factorial aerobic scope (FAS) should be inversely correlated with Pc across species and temperatures, and this was supported by data on species where Pc and FAS is measured (left panel), leading to the notion that Pc may be an adaptation for AS. In *Centropristris striata* (right panel, Seibel and Deutsch, 2020; Slesinger et al., 2019), Pc increases with temperature due to the faster rise in SMR compared to MMR, equalling normoxic oxygen tension when SMR has caught up with MMR. In *C. striata*, Pc increases with temperature but would not reach normoxia at temperatures where individuals can still live. Similarly, extrapolation of the temperature coefficients for SMR and MMR suggests they would become equal at extremely high temperatures (> 60 °C) where

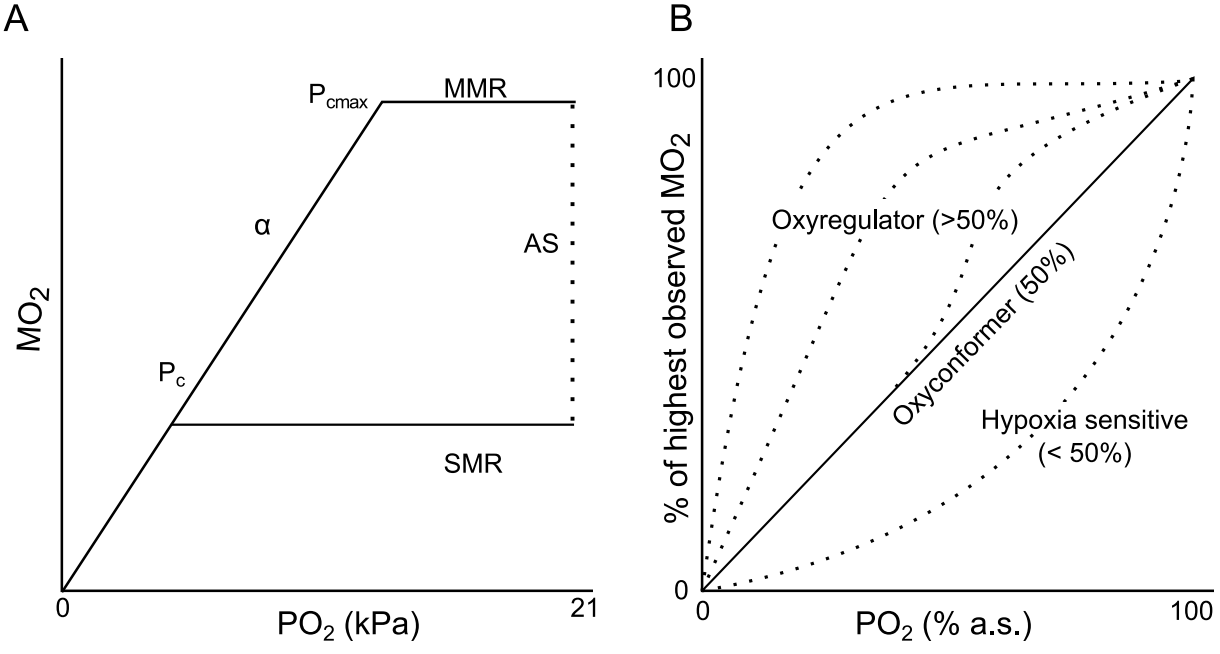
individuals clearly cannot survive. The authors reinterpret declining MMR (MMRmeas) beyond a certain temperature as thermal limitation, rather than oxygen-related, as organisms are modelled to still have a functional oxygen supply capacity. Previous measurements also show declines in MMR and AAS, without an increase in Pc (see Slesinger et al., 2019). The model opens up novel avenues of research, as its hypotheses are quantitative, making them testable/falsifiable. For example, Pcmax still awaits widespread direct measurement, as the authors note, but the notions that (1) Pcmax is constrained near normoxia regardless of temperature (for normoxic species) and that (2) Pcmax matches the prevailing environmental PO_2, are both readily testable ideas.

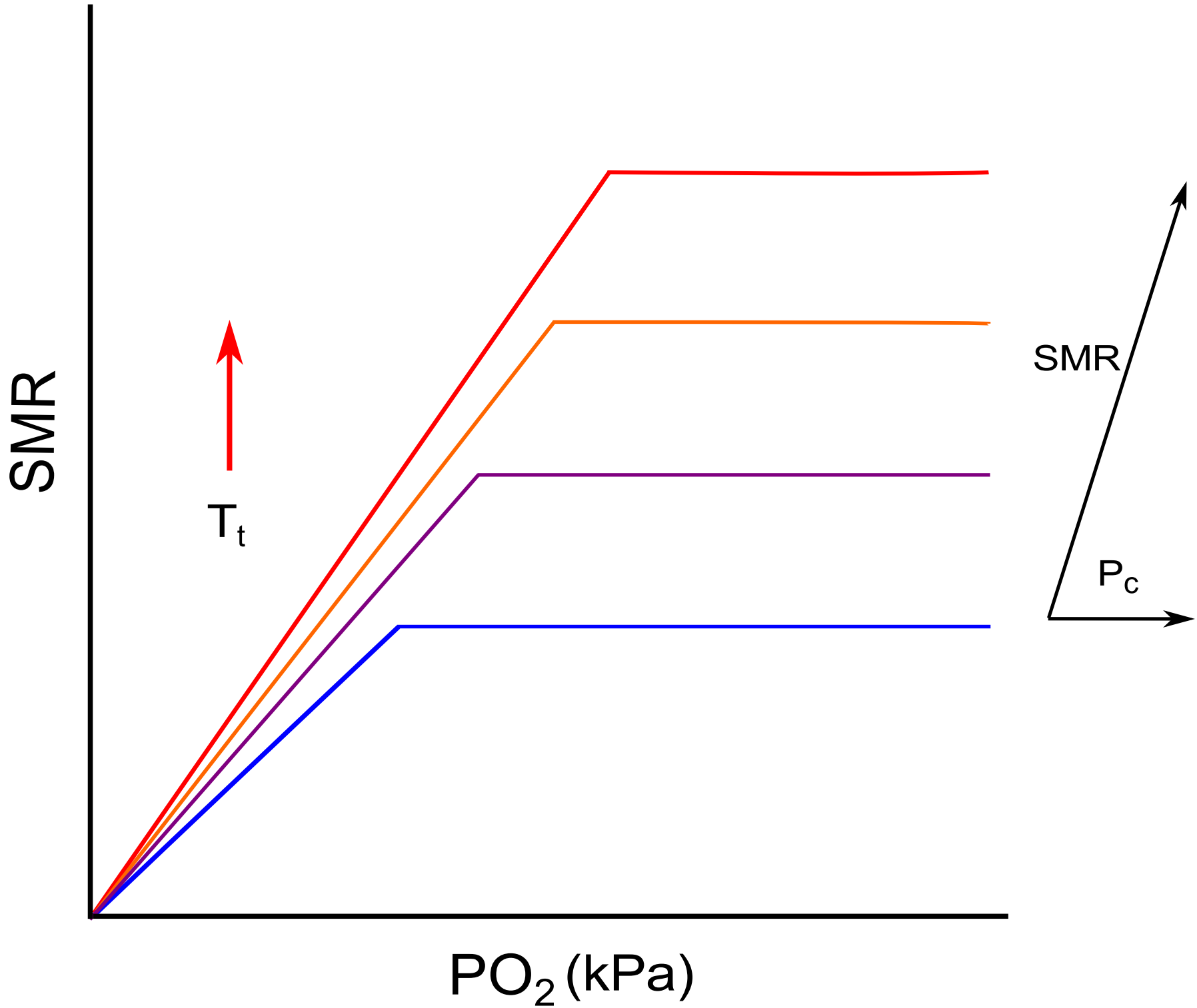


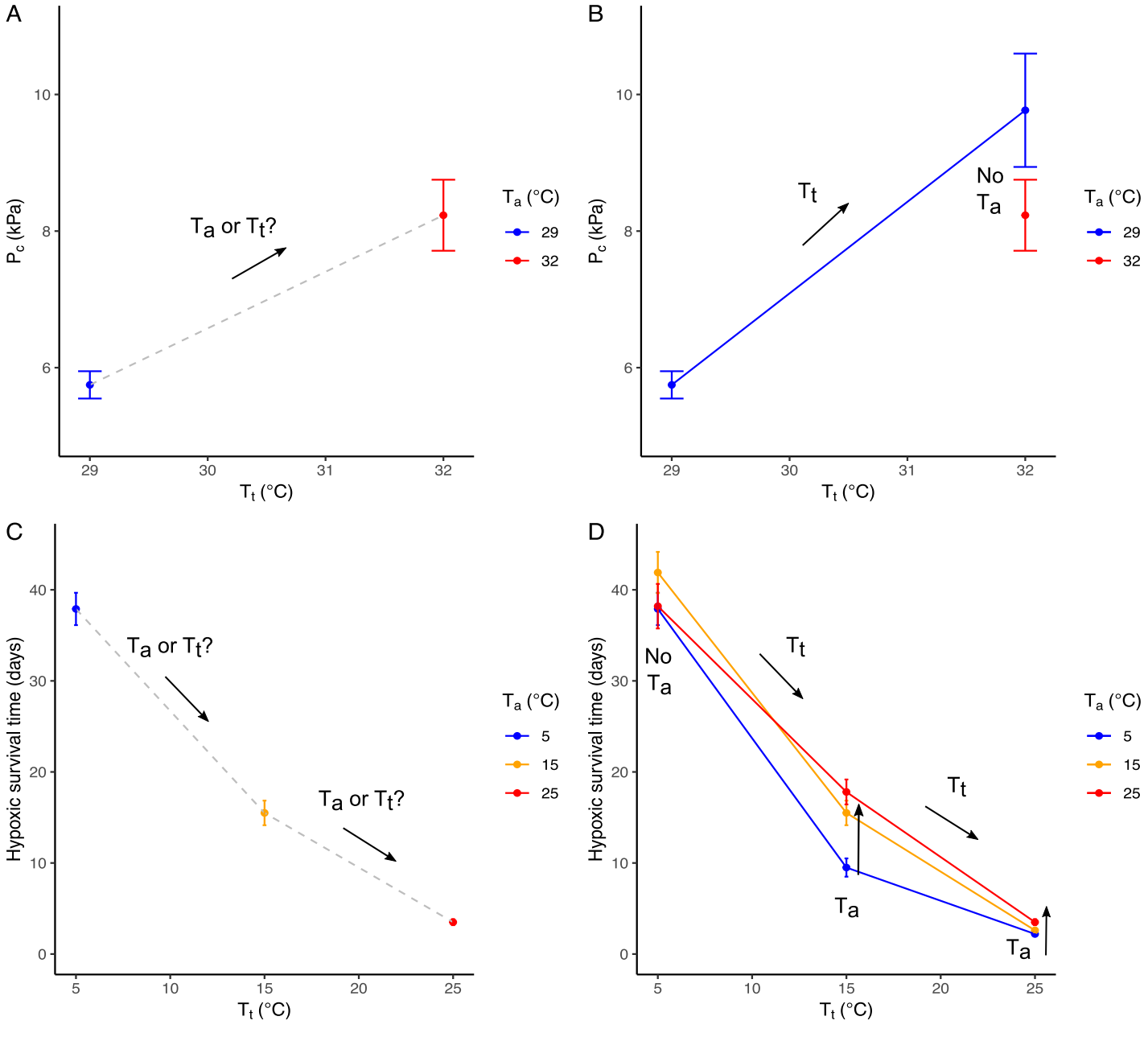


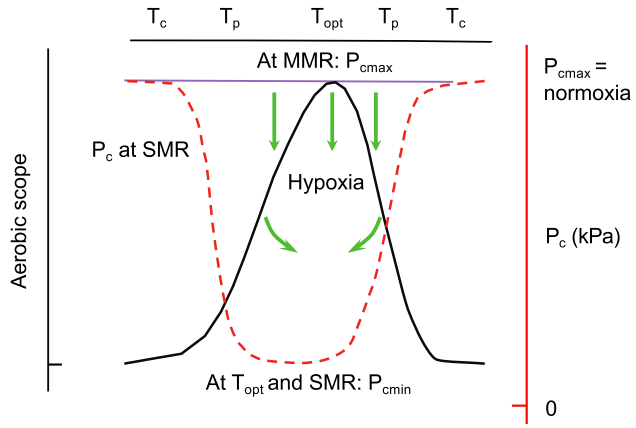


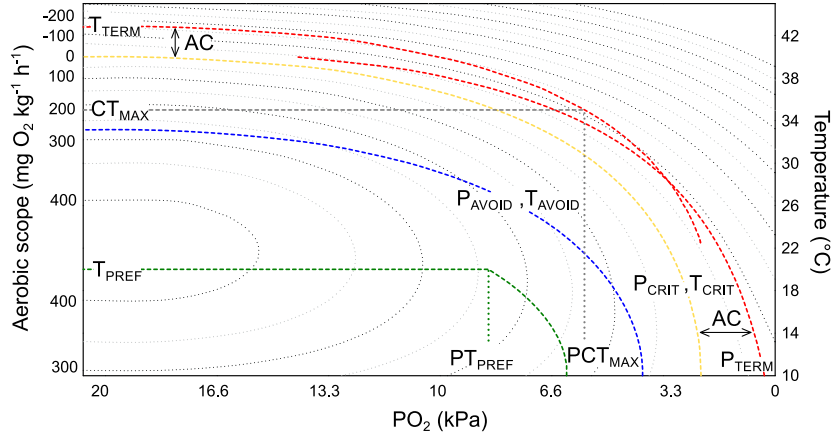
Hypoxic performance measured in:
i non-acclimated individuals at ambient temperature
ii non-acclimated individuals exposed to warming
iii acclimated individuals at ambient temperature
iv acclimated individuals exposed to warming

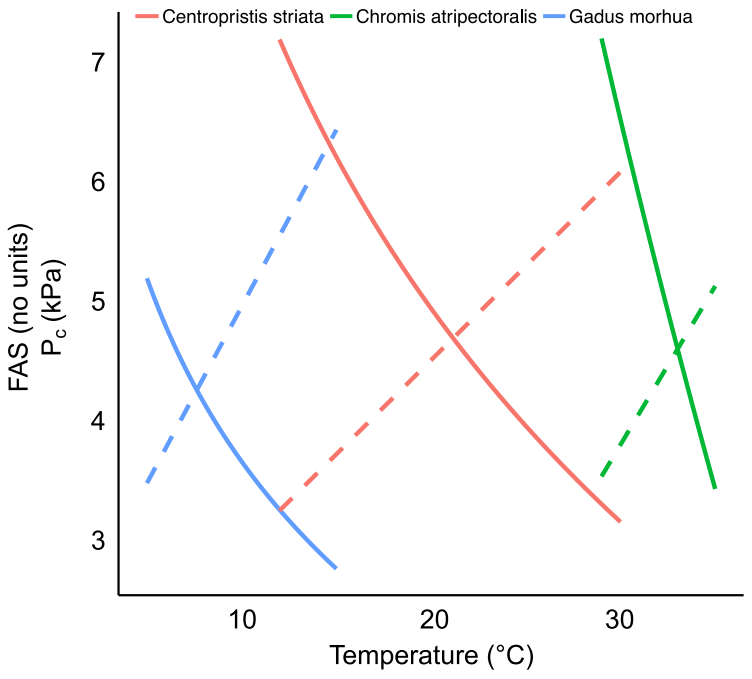

A
P_{cmax}
MMR
α
AS
MO_2
P_c
SMR
0
PO_2 (kPa)
21
B
100
% of highest observed MO_2
Oxyregulator (>50%)
Oxyconformer (50%)
Hypoxia sensitive
(< 50%)
0
0
PO_2 (% a.s.)
100

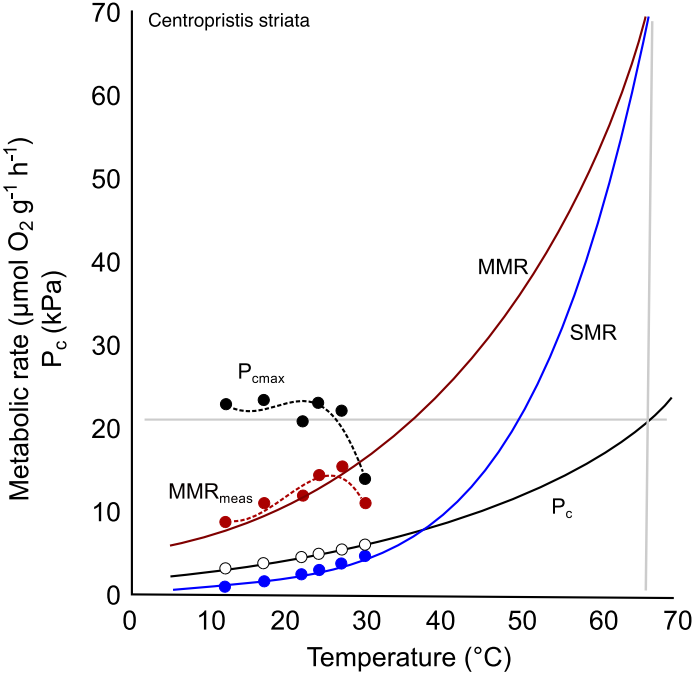

SMR
T_t
PO_2 (kPa)
SMR
P_c


A
B
C
D
P_c (kPa)
T_t (°C)
T_a or T_t?
T_t
No T_a
T_a
Hypoxic survival time (days)
T_a (°C)
29
32
5
15
25


T_c
T_p
T_{opt}
T_p
T_c
At MMR: P_{cmax}
P_c at SMR
Hypoxia
At T_{opt} and SMR: P_{cmin}
Aerobic scope
P_{cmax} = normoxia
P_c (kPa)
0


T_{TERM}
AC
CT_{MAX}
P_{AVOID} , T_{AVOID}
T_{PREF}
P_{CRIT} , T_{CRIT}
AC
PT_{PREF}
PCT_{MAX}
P_{TERM}
Aerobic scope (mg O_2 kg^{-1} h^{-1})
-200
-100
0
100
200
300
400
400
300
Temperature (°C)
42
38
34
30
26
22
18
14
10
20
16.6
13.3
10
6.6
3.3
0
PO_2 (kPa)


Centropristis striata
Chromis atripectoralis
Gadus morhua
FAS (no units)
P_c (kPa)
7
6
5
4
3
10
20
30
Temperature (°C)


Centropristis striata
Metabolic rate (µmol O_2 g^{-1} h^{-1})
P_c (kPa)
70
60
50
40
30
20
10
0
MMR
SMR
P_{cmax}
MMR_{meas}
P_c
0
10
20
30
40
50
60
70
Temperature (°C)