



**HAL**  
open science

# In a marine teleost, the significance of oxygen supply for acute thermal tolerance depends upon the context and the endpoint used

Julie Nati, Felipe Blasco, Charles Rodde, Alain Vergnet, François Allal, Marc Vandeputte, David Mckenzie

## ► To cite this version:

Julie Nati, Felipe Blasco, Charles Rodde, Alain Vergnet, François Allal, et al.. In a marine teleost, the significance of oxygen supply for acute thermal tolerance depends upon the context and the endpoint used. *Journal of Experimental Biology*, 2023, 226 (11), pp.jeb245210. 10.1242/jeb.245210 . hal-04100080

**HAL Id: hal-04100080**

**<https://hal.umontpellier.fr/hal-04100080>**

Submitted on 9 Nov 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



16 **Abstract**

17 Eight juvenile European seabass were exposed to two thermal ramping protocols with different  
18 levels of aerobic activity and tolerance endpoint: the critical thermal maximum for swimming  
19 ( $CTS_{max}$ ) while exercising aerobically until fatigue, and the critical thermal maximum ( $CT_{max}$ ) under  
20 static conditions until loss of equilibrium (LOE). In the  $CTS_{max}$ , warming caused a profound increase in  
21 oxygen uptake rate ( $\dot{M}O_2$ ) culminating in a gait transition, from steady aerobic towards unsteady  
22 anaerobic swimming, then fatigue at  $30.3 \pm 0.4^\circ C$  (mean  $\pm$  SE). Gait transition and fatigue  
23 presumably indicate an oxygen limitation, an inability to meet the combined demands of swimming  
24 plus warming. The  $CT_{max}$  also elicited an increase in  $\dot{M}O_2$ , culminating in LOE at  $34.0 \pm 0.4^\circ C$ ,  
25 significantly warmer than fatigue at  $CTS_{max}$ . The maximum  $\dot{M}O_2$  achieved in the  $CT_{max}$  was, however,  
26 less than 30% of that achieved in the  $CTS_{max}$ . Therefore, the static  $CT_{max}$  did not exploit full  
27 cardiorespiratory capacity for oxygen supply, indicating that LOE was not caused by systemic oxygen  
28 limitation. Consequently, systemic oxygen supply can be significant for tolerance of acute warming  
29 in seabass but this depends upon the physiological context and the endpoint used.

30

31 **Keywords:** critical thermal maximum, fish, oxygen uptake, swimming

32

33

34

35

## 36 Introduction

37 Global warming will cause a rise in sea surface temperatures of up to 4°C by 2100, accompanied by  
38 increased frequency and severity of acute heat waves (Frölicher et al., 2018) . Temperature has  
39 direct thermodynamic effects on the physiology of ectotherms, so there has been extensive research  
40 to investigate thermal tolerance limits in fishes, and the underlying mechanisms. The Fry paradigm  
41 and Oxygen and Capacity Limited Thermal Tolerance hypothesis (Fry-OCLTT) have been proposed as  
42 a universal principle underlying thermal tolerance in ectotherms (Fry, 1971; Pörtner, 2010).  
43 According to the Fry-OCLTT, oxygen demands of metabolism are accelerated inexorably by warming  
44 until they exceed cardiorespiratory capacity for oxygen supply, causing functional collapse (Eliason  
45 et al., 2011; Fry, 1971; Pörtner, 2010; Pörtner and Farrell, 2008; Schulte, 2015). Empirical evidence  
46 for the Fry-OCLTT paradigm is, however, mixed (Farrell, 2016; Jutfelt et al., 2018; Lefevre, 2016;  
47 Lefevre et al., 2021; Pörtner, 2021).

48         There is particular uncertainty about the role of oxygen limitation in tolerance of acute  
49 warming in fishes. Acute thermal tolerance is typically measured with the critical thermal maximum  
50 ( $CT_{max}$ ) protocol, where fish are warmed in steps until loss of equilibrium (LOE) (Lutterschmidt and  
51 Hutchison, 1997). The LOE at  $CT_{max}$  is an incipient lethal endpoint due to dysfunction of critical  
52 organs, brain and heart (Andreassen et al., 2022; Lefevre et al., 2021; Rezende et al., 2011). In some  
53 fish species, environmental oxygen availability and/or blood oxygen carrying capacity have little or  
54 no effect on  $CT_{max}$ , indicating that LOE is not oxygen dependent (Brijs et al., 2015; Ern et al., 2016;  
55 McArley et al., 2021). In other species, measurements of rates of oxygen uptake ( $\dot{M}O_2$ ) during a  
56  $CT_{max}$  protocol found an initial exponential increase up to a maximum that was comparable to their  
57 maximum metabolic rate measured at initial acclimation temperature. This was then followed by a  
58 plateau and/or decline, which preceded LOE and which might indicate a limitation in capacity for  
59 tissue oxygen supply prior to the endpoint (McArley et al., 2017; Norin et al., 2019). The contrasting  
60 evidence indicates that LOE at  $CT_{max}$  may have many underlying mechanisms, which may or may not  
61 be linked to oxygen limitation, and which differ among species, methodology and context  
62 (Andreassen et al., 2022; Ern et al., 2023; Lefevre et al., 2021; Rezende et al., 2014).

63         In a study to investigate effects of acute temperature increases on cardiorespiratory  
64 performance of sockeye salmon (*Oncorhynchus nerka*), Steinhausen et al. (2008) warmed fish  
65 progressively while they swam aerobically in a swim tunnel. A number of salmon showed a gait-  
66 transition to an anaerobic swimming mode and then fatigued at warm temperatures, which the  
67 authors attributed to an inability to meet the combined oxygen demands of swimming plus warming  
68 (Steinhausen et al., 2008). Blasco et al. (2020) proposed that a similar protocol could be used to  
69 evaluate acute thermal tolerance in fishes, warming in steps with fatigue as the endpoint. In two

70 tropical freshwater teleosts exercising aerobically in a swim tunnel, progressive warming caused  
71 profound increases in  $\dot{M}O_2$ , to levels very significantly higher than the individuals' maximum  
72 metabolic rate during a critical swimming speed ( $U_{crit}$ ) test at their acclimation temperature. At a  
73 certain warm temperature, however, all individuals transitioned from a steady aerobic to an  
74 unsteady anaerobic gait and then fatigued, at temperatures significantly lower than their LOE at  
75  $CT_{max}$  (Blasco et al., 2020). Dubbed the critical thermal maximum for swimming ( $CTS_{max}$ ) by Blasco et  
76 al. (2022), the mechanism underlying fatigue would presumably be oxygen supply limitation, an  
77 inability to meet the combined oxygen demands of swimming plus warming (Blasco et al., 2020;  
78 Blasco et al., 2022; Steinhausen et al., 2008).

79 Here, we investigated the general hypothesis that capacity for tissue oxygen supply can play  
80 a role in acute upper thermal tolerance in fishes, but that this depends upon the prevailing level of  
81 aerobic metabolic activity and consequent oxygen demand, and the tolerance endpoint used. We  
82 studied the European seabass *Dicentrarchus labrax*, a temperate marine teleost that has been the  
83 focus of investigations into the role of oxygen supply in defining  $CT_{max}$  (Anttila et al., 2023; Wang et  
84 al., 2014). We compared  $\dot{M}O_2$  during a  $CTS_{max}$  and  $CT_{max}$  protocol in the same individuals, in  
85 particular the maximum  $\dot{M}O_2$  achieved prior to each tolerance endpoint, fatigue or LOE. We  
86 reasoned that, if in the  $CTS_{max}$  protocol the seabass transitioned to unsteady anaerobic swimming at  
87 a certain warm temperature, and then fatigued, then capacity for tissue oxygen supply would  
88 underly this thermal tolerance endpoint in this species, as for the species studied by Blasco et al.  
89 (2020). We expected that LOE at  $CT_{max}$  would occur at a significantly higher temperature than  
90 fatigue at  $CTS_{max}$ , as observed previously (Blasco et al., 2020; Blasco et al., 2022). We, however,  
91 investigated the specific hypothesis that maximum  $\dot{M}O_2$  elicited by the  $CT_{max}$  would be significantly  
92 less than those in the  $CTS_{max}$ , indicating that the LOE endpoint was not caused by limitations in  
93 capacity for systemic tissue oxygen supply in this species (Wang et al., 2014).

#### 94 **Material and Methods**

95 Juvenile seabass were obtained from a population at the Station Ifremer de Palavas-les-Flots  
96 (France), reared in seawater at 18 – 19 °C and tagged (PIT, under benzocaine anaesthesia) for  
97 individual identification. Fish were held in a 1 m<sup>3</sup> tank supplied with biofiltered seawater at 18 °C for  
98 at least two weeks prior to experimentation, fed a maintenance ration with commercial pellets but  
99 fasted for 24 h before experiments. Prior to the main trials, a control was performed at 18 °C on six  
100 seabass of mean ( $\pm$  SE) mass 111.4  $\pm$  9.1 g and forklength 202  $\pm$  6 mm, which were swum at the  
101 speed of the  $CTS_{max}$  (2.5 BL s<sup>-1</sup>) for 8 h. For the  $CTS_{max}$  and  $CT_{max}$ , eight seabass were studied, of mean  
102 mass 74.2  $\pm$  8.0 and forklength 181  $\pm$  6 mm at the  $CTS_{max}$ , then mean mass 75.3  $\pm$  8 g at the  $CT_{max}$ .

103 Swimming trials were performed in a plexiglass Steffensen-type swim tunnel (volume 30 l)  
104 provided with biofiltered aerated seawater at 18 °C. Fish were measured for mass, width, height,  
105 and fork length, to calculate relative swimming speed in body length per second ( $\text{BL s}^{-1}$ ) corrected for  
106 solid blocking effect (Bell and Terhune, 1970), then acclimated overnight at a low swimming speed of  
107  $1 \text{ BL s}^{-1}$ . The next day, current speed was increased by  $0.25 \text{ BL s}^{-1}$  every 2 min until  $2.5 \text{ BL s}^{-1}$ . In the  
108 control trial, the fish then swam for 8h. In the  $\text{CTS}_{\text{max}}$ , after 30 min at 18 °C the temperature was  
109 increased by 1°C each 30 min until fish fatigued, resting their tails for at least 10 s against the rear  
110 grid. Fish were immediately removed from the tunnel into a tub of aerated seawater at 18°C for 30  
111 min, then returned to their holding tank.  $\text{CTS}_{\text{max}}$  was calculated as the last temperature step fully  
112 completed plus the proportion of the ultimate step prior to fatigue (Blasco et al., 2020). The  
113 experiments were performed over three weeks, with the last individual studied 24h before  
114 measurement of its  $\text{CT}_{\text{max}}$  (below).

115 The  $\text{CT}_{\text{max}}$  was performed in eight individual respirometry chambers (volume 3 l) that were  
116 supplied with aerated seawater at 19 °C, due to an overnight increase in the surface temperature of  
117 the local seawater supplying the facilities. Fish were acclimated to the chambers overnight then, the  
118 next morning, temperature was increased by 1°C every 30 min until LOE (McArley et al., 2017;  
119 Penney et al., 2014). Chambers were screened from view with an opaque plastic sheet containing a  
120 small observation hole, to monitor fish throughout. As soon as fish lost dorso-ventral equilibrium,  
121 they were removed and placed in aerated water at 19 °C for 30 min, then returned to their holding  
122 tank.  $\text{CT}_{\text{max}}$  was calculated as for  $\text{CTS}_{\text{max}}$  but using LOE as endpoint (Blasco et al., 2020).

123 The  $\dot{\text{M}}\text{O}_2$  was measured in  $\text{mgO}_2 \text{ kg}^{-1} \text{ h}^{-1}$  over the last 10 min of each temperature increment,  
124 in both protocols, by intermittent-flow respirometry (Blasco et al., 2020; Steffensen, 1989).  $\dot{\text{M}}\text{O}_2$  was  
125 corrected for body mass with a scaling coefficient of  $b = 0.8$  for metabolic rate in European seabass  
126 (Rodde et al., 2021). The maximum  $\dot{\text{M}}\text{O}_2$  achieved in each protocol was identified for each individual.  
127 Absolute thermal scope for  $\text{CT}_{\text{max}}$  and  $\text{CTS}_{\text{max}}$  was calculated as maximum  $\dot{\text{M}}\text{O}_2$  minus the relevant  
128  $\dot{\text{M}}\text{O}_2$  at 19°C. The proportional change in  $\dot{\text{M}}\text{O}_2$  was calculated as a  $Q_{10}$  value over 19 – 29°C.

129 A two-way ANOVA with repeated measures was used to evaluate effects of temperature on  
130  $\dot{\text{M}}\text{O}_2$ , with one factor protocol ( $\text{CTS}_{\text{max}}$  versus  $\text{CT}_{\text{max}}$ ), repeated factor the temperature increments,  
131 each fish as an individual, and an interaction term between protocol and temperature steps. Data  
132 were considered for a range of 19 to 30°C, which was measured on all individuals in both protocols.  
133 An error function was included to correct for repeated tests on the same individual. Tukey post hoc  
134 tests, with Holm correction for multiple comparisons, were used to identify the temperature at  
135 which  $\dot{\text{M}}\text{O}_2$  first increased significantly from the value at 19 °C, and to compare  $\dot{\text{M}}\text{O}_2$  between  
136 protocols at each temperature. Single variables, such as  $\text{CTS}_{\text{max}}$  and  $\text{CT}_{\text{max}}$ , maximum  $\dot{\text{M}}\text{O}_2$ , thermal

137 scope, and  $Q_{10}$  were compared by pairwise Welch t-tests. All statistical analyses were performed in R  
138 4.0.2 within the lsmeans package (version 2.27-61), with significance accepted at  $p < 0.05$ .

## 139 **Results**

140 At a speed of  $2.5 \text{ BL s}^{-1}$ , the seabass swam with a sustained aerobic body-caudal swimming gait. In  
141 the control trial the seabass swam for 8h with no sign whatsoever of fatigue. During  $\text{CTS}_{\text{max}}$ , all  
142 individuals eventually transitioned in swimming gait, from an entirely steady aerobic gait with  
143 rhythmic beating of the tail, to increasing engagement of unsteady anaerobic 'burst-and-coast'  
144 episodes. This led to fatigue within less than one temperature increment (30 min). No fish lost  
145 equilibrium in the swimming trials. During  $\text{CT}_{\text{max}}$ , the fish exhibited erratic behaviour, rolling  
146 sideways, then complete loss of dorsoventral orientation. The mean  $\text{CTS}_{\text{max}}$  was  $30.3 \pm 0.4^\circ\text{C}$ ,  
147 significantly and almost  $4^\circ\text{C}$  lower than mean  $\text{CT}_{\text{max}}$  at  $34.0 \pm 0.4^\circ\text{C}$  (Figure 1A).

148 In the control swim,  $\dot{M}\text{O}_2$  remained stable for 8h (Figure S1, supplementary materials).  
149 caused There were marked increases in  $\dot{M}\text{O}_2$  in both thermal ramping protocols (Figure 2), that  
150 became significant from  $19^\circ\text{C}$  at  $25^\circ\text{C}$  in both cases. There was, however, a significant interaction  
151 between protocol and temperature (Two-way ANOVA,  $F_{11,74}=13.71$ ,  $p < 0.001$ ). All measures of  $\dot{M}\text{O}_2$   
152 in  $\text{CTS}_{\text{max}}$ , irrespective of temperature, were higher than any measure of  $\dot{M}\text{O}_2$  in the  $\text{CT}_{\text{max}}$  (Two-way  
153 ANOVA, Holm  $p < 0.001$ , Table S1, supplementary materials). Consequently, the maximum  $\dot{M}\text{O}_2$   
154 achieved and absolute thermal scope were significantly higher in the  $\text{CTS}_{\text{max}}$  (Figure 1). Despite  
155 these differences in  $\dot{M}\text{O}_2$  and absolute thermal scope,  $Q_{10}$  did not in fact differ between protocols  
156 (Figure 1).

157

## 158 **Discussion**

159 The results demonstrate that capacity for tissue oxygen supply can be significant for upper thermal  
160 tolerance in this teleost species, but this depends upon the physiological context and the tolerance  
161 endpoint used. When warmed while exercising aerobically, all individuals eventually transitioned to  
162 unsteady anaerobic swimming, evidence of limitations in capacity for tissue oxygen supply  
163 (Steinhausen et al., 2008), leading to fatigue at  $\text{CTS}_{\text{max}}$ . When warmed under static conditions, the  
164 animals eventually lost equilibrium at a  $\text{CT}_{\text{max}}$  that was significantly higher than their  $\text{CTS}_{\text{max}}$  but, in  
165 line with our specific hypothesis, maximum  $\dot{M}\text{O}_2$  in the  $\text{CT}_{\text{max}}$  was very significantly less than achieved  
166 in the  $\text{CTS}_{\text{max}}$ . Therefore, the full cardiorespiratory capacity for oxygen supply was not exploited  
167 during thermal ramping in the static  $\text{CT}_{\text{max}}$ , indicating that LOE is not linked to limitations in systemic  
168 oxygen delivery in this species (Wang et al., 2014).

169 Fatigue in the  $\text{CTS}_{\text{max}}$  was not due to limited aerobic endurance because, at their acclimation  
170 temperature, seabass swam at  $2.5 \text{ BL s}^{-1}$  for longer than the duration of the warming challenge.

171 Similar aerobic endurance was observed in Nile tilapia *Oreochromis niloticus* and pacu *Piaractus*  
172 *mesopotamicus* (Blasco et al., 2020). This confirms that the fatigue endpoint in the  $CTS_{max}$  is due to  
173 the progressive warming. The swimming responses to the  $CTS_{max}$  protocol, gait transition followed by  
174 fatigue, were also very similar in tilapia and pacu (Blasco et al., 2020). The gait transition is  
175 qualitatively indistinguishable to that observed prior to fatigue in a critical swimming speed ( $U_{crit}$ )  
176 protocol, where it is stimulated by increments in current velocity rather than temperature. This  
177 indicates that the transition occurs due to a similar mechanism. In the  $U_{crit}$ , it is typically assumed  
178 that gait transition and then fatigue occur because a fish has reached its maximum cardiorespiratory  
179 capacity for oxygen supply (Brett, 1964; Claireaux et al., 2005; Farrell, 2007; Webb, 1998). Although  
180 it is not known what causes the gait transition in a  $U_{crit}$  test, one plausible theory focuses on the  
181 heart. An aerobic organ, the teleost heart receives much of its oxygen supply from venous return in  
182 the single circulation, after the blood has unloaded oxygen to respiring tissues (Farrell and Jones,  
183 1992; Jones and Randall, 1978). It has been suggested that during an incremental swim challenge,  
184 fishes engage the gait transition towards anaerobic swimming when tissue oxygen extraction  
185 outstrips capacity for supply, and oxygen levels in venous blood returning to the heart drop below a  
186 critical level. By engaging the white muscle, the fish reduces rates of oxygen extraction by the  
187 working red muscle and so venous oxygen supply to the heart is assured (Farrell and Clutterham,  
188 2003; McKenzie and Claireaux, 2010). The gait transition preceding fatigue in the  $CTS_{max}$  may reflect  
189 a similar decline in venous oxygen levels, that risked compromising oxygen supply to the working  
190 heart (Blasco et al., 2020).

191 Steinhausen et al., (2008) found that fatigue from exercise during acute warming in the  
192 sockeye salmon coincided with cardiac pumping capacity reaching its maximum. Cardiac  
193 performance plays a major role in defining acute thermal tolerance in many fish species (Ekström et  
194 al., 2014; Ekström et al., 2016; Farrell, 2007; Gilbert et al., 2019), so represents a focus for future  
195 studies regarding the mechanisms for the  $CTS_{max}$  endpoint. Other mechanisms may also contribute,  
196 progressive warming can impair locomotor coordination in fishes, possibly as a consequence of  
197 limitation in oxygen supply to the brain (Andreassen et al., 2022). Further research is therefore  
198 required to understand what causes gait transition and fatigue in a  $CTS_{max}$  but it is interesting that  
199 the test solicits similar physiological responses in multiple species (Blasco et al., 2020).

200 Although the  $CTS_{max}$  results provide evidence that tissue oxygen supply can play a role in  
201 thermal tolerance in swimming seabass when fatigue is the endpoint, the  $CT_{max}$  data support the  
202 hypothesis that LOE is not due to limitations in systemic oxygen supply in this species (Wang et al.,  
203 2014). The mean  $CT_{max}$  of 34.0 °C in our juvenile seabass reared at 18° C, was comparable to previous  
204 reports of 34.7 and 35.6 °C for juveniles acclimated for 30 days to 15 or 20 °C, respectively (Kir and



205 Demirci, 2018). The slightly higher  $CT_{max}$  reported by Kir and Demirci (2018) may also be linked to a  
206 more rapid thermal ramping of  $0.3\text{ }^{\circ}\text{C min}^{-1}$  compared to  $0.033\text{ }^{\circ}\text{C min}^{-1}$  in this study, as more rapid  
207 ramping is known to lead to higher  $CT_{max}$  values in fishes (Desforges et al., 2023; Ern et al., 2023). We  
208 ramped at  $1^{\circ}\text{C}$  every 30 min to ensure that fish core temperature was equilibrated with the water at  
209 each step, and that we could measure  $M_{O_2}$  over the last 10 min. While  $M_{O_2}$  increased markedly with  
210 warming in the static  $CT_{max}$ , as observed in other studies (McArley et al., 2017; Norin et al., 2019),  
211 and the  $Q_{10}$  was similar in both protocols, the actual rates were always significantly lower than at  
212 any temperature in the  $CTS_{max}$ . That is, LOE occurred at  $M_{O_2}$  levels lower than those of the same  
213 individuals exercising at  $2.5\text{ BL s}^{-1}$  at  $19\text{ }^{\circ}\text{C}$ . Static respirometry does not constrain gas exchange in  
214 seabass, juveniles achieved similar high maximum rates of oxygen uptake when either swum in a  $U_{crit}$   
215 test or chased to exhaustion and then placed in a static chamber (Killen et al., 2017). Therefore,  
216 warming did not challenge capacity for oxygen supply in stationary fish, it caused LOE by an oxygen-  
217 independent mechanism. There are a variety of possible contenders, particularly direct temperature-  
218 induced effects on critical organs such as heart and brain, which cause their dysfunction. There is  
219 evidence of this in fishes, including that such effects can interact with oxygen limitation within these  
220 organs (Andreassen et al., 2022; Friedlander et al., 1976; Vornanen, 2020). Overall, the consensus is  
221 that LOE can have multiple causes and that systemic oxygen limitation is not a universal mechanism  
222 across fish species (Andreassen et al., 2022; Ern et al., 2023; McArley et al., 2021).

223 The Fry-OCLTT argues that capacity for oxygen supply is a mechanism underlying thermal  
224 tolerance in fishes (Fry, 1971; Pörtner, 2010), the  $CTS_{max}$  test indicates that it can be in multiple  
225 species, if fatigue from aerobic activity is the tolerance endpoint. Here we show that this is true for  
226 a species where LOE in a  $CT_{max}$  protocol appears to occur by an oxygen-independent mechanism. The  
227  $CT_{max}$  is easy and rapid to perform but the endpoint has a complex multitude of potential  
228 mechanisms. The  $CTS_{max}$  is more technically demanding but the mechanism underlying tolerance  
229 may be similar across fish species.

### 230 **Acknowledgements**

231 We are grateful to two anonymous referees for comments that significantly improved the  
232 presentation of this manuscript.

### 233 **Ethics.**

234 Experimental procedures were approved by the ethics committee for animal experimentation n° 036  
235 of the French Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation, with  
236 reference number APAFIS#19567-2018100910598940 v2.

237 **Data accessibility.** Data are available in the electronic supplementary material

238 **Author contribution.** All authors contributed to study conception, design, securing funding, animal  
239 husbandry. J.J.H.N., F.R.B. and C.R. carried out the experiments and completed the data analyses.  
240 J.J.H.N and D.J.M. drafted the initial manuscript; all authors then reviewed and revised the  
241 manuscript.

242 **Competing interests.** We declare no competing interests.

243 **Funding.** J.J.H.N. was funded by an individual Marie Curie Fellowship (MSCA-IF-EF-ST 839038,  
244 INDITOL), F.R.B. was supported by the AquaExcel Transnational<sup>2020</sup> Access project AE120016  
245 PhenoBass and by a Company of Biologists Travel Grant. The research was also supported by the  
246 FEAMP Measure n° 47 Aquaculture Innovation project SELFIE.

247

## 248 **References**

249 **Andreassen, A. H., Hall, P., Khatibzadeh, P., Jutfelt, F. and Kermen, F. (2022).** Brain  
250 dysfunction during warming is linked to oxygen limitation in larval zebrafish. *Proc.*  
251 *Natl. Acad. Sci.* **119**, e2207052119.

252 **Bell, W. H. and Terhune, L. D. B. (1970).** Water tunnel design for fisheries research. *Fish.*  
253 *Resour. Board Can. Tech. Rep.* **195**, 1–69.

254 **Blasco, F. R., Esbaugh, A. J., Killen, S. S., Rantin, F. T., Taylor, E. W. and McKenzie, D. J.**  
255 (2020). Using aerobic exercise to evaluate sub-lethal tolerance of acute warming in  
256 fishes. *J. Exp. Biol.* **223**,

257 **Blasco, F. R., Taylor, E. W., Leite, C. A. C., Monteiro, D. A., Rantin, F. T. and McKenzie, D. J.**  
258 (2022). Tolerance of an acute warming challenge declines with body mass in Nile  
259 tilapia: evidence of a link to capacity for oxygen uptake. *J. Exp. Biol.* **225**, jeb244287.

260 **Brett, J. R. (1964).** The respiratory metabolism and swimming performance of young  
261 sockeye salmon. *J. Fish. Res. Board Can.* **21**, 1183–1226.

262 **Brijs, J., Jutfelt, F., Clark, T. D., Grans, A., Ekstrom, A. and Sandblom, E. (2015).**  
263 Experimental manipulations of tissue oxygen supply do not affect warming tolerance  
264 of European perch. *J. Exp. Biol.* **218**, 2448–2454.

265 **Claireaux, G., McKenzie, D. J., Genge, a G., Chatelier, A., Aubin, J. and Farrell, A. P. (2005).**  
266 Linking swimming performance, cardiac pumping ability and cardiac anatomy in  
267 rainbow trout. *J. Exp. Biol.* **208**, 1775–84.

268 **Desforges, J. E., Birnie-Gauvin, K., Jutfelt, F. M., Gilmour, K. M., Eliason, E. J., Dressler, T.**  
269 **L., McKenzie, D. J., Bates, A. E., Lawrence, M. J., Fangue, N. A., et al. (2023).** The  
270 ecological relevance of critical thermal maxima methodology (CTM) for fishes. *J. Fish*  
271 *Biol.* **00**,

- 272 **Ekström, A., Jutfelt, F. and Sandblom, E.** (2014). Effects of autonomic blockade on acute  
 273 thermal tolerance and cardioventilatory performance in rainbow trout,  
 274 *Oncorhynchus mykiss*. *J. Therm. Biol.* **44**, 47–54.
- 275 **Ekström, A., Brijs, J., Clark, T. D., Gräns, A., Jutfelt, F. and Sandblom, E.** (2016). Cardiac  
 276 oxygen limitation during an acute thermal challenge in the European perch: effects  
 277 of chronic environmental warming and experimental hyperoxia. *Am. J. Physiol.-*  
 278 *Regul. Integr. Comp. Physiol.* **311**, R440–R449.
- 279 **Eliason, E. J., Clark, T. D., Hague, M. J., Hanson, L. M., Gallagher, Z. S., Jeffries, K. M., Gale,**  
 280 **M. K., Patterson, D. A., Hinch, S. G. and Farrell, A. P.** (2011). Differences in thermal  
 281 tolerance among sockeye salmon populations. *Science* **332**, 109–12.
- 282 **Ern, R., Norin, T., Gamperl, A. K. and Esbaugh, A. J.** (2016). Oxygen dependence of upper  
 283 thermal limits in fishes. *J. Exp. Biol.* **219**, 3376–3383.
- 284 **Ern, R., Andreassen, A. H. and Jutfelt, F.** (2023). Physiological mechanisms of acute upper  
 285 thermal tolerance in fish. *Physiology*.
- 286 **Farrell, A. P.** (2007). Cardiorespiratory performance during prolonged swimming tests with  
 287 salmonids: a perspective on temperature effects and potential analytical pitfalls.  
 288 *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **362**, 2017–30.
- 289 **Farrell, A. P.** (2016). Pragmatic perspective on aerobic scope: Peaking, plummeting, pejus  
 290 and apportioning. *J. Fish Biol.* **88**, 322–343.
- 291 **Farrell, A. P. and Clutterham, S. M.** (2003). On-line venous oxygen tensions in rainbow trout  
 292 during graded exercise at two acclimation temperatures. *J. Exp. Biol.* **206**, 487–496.
- 293 **Farrell, A. P. and Jones, D. R.** (1992). The heart. In *Fish Physiology Volume 12A* (ed. Hoar, W.  
 294 S.), Randall, D. J.), and Farrell, A. P.), pp. 1–88.
- 295 **Friedlander, M. J., Kotchabhakdi, N. and Prosser, C. L.** (1976). Effects of cold and heat on  
 296 behavior and cerebellar function in goldfish. *J. Comp. Physiol.* ■ **A 112**, 19–45.
- 297 **Frölicher, T. L., Fischer, E. M. and Gruber, N.** (2018). Marine heatwaves under global  
 298 warming. *Nature* **560**, 360–364.
- 299 **Fry, F. E. J.** (1971). The Effect of Environmental Factors on the Physiology of Fish. In *Fish*  
 300 *Physiology Volume 6* (ed. Hoar, W. S.) and Randall, D. J.), pp. 1–98. New York:  
 301 Academic Press.
- 302 **Gilbert, M. J. H., Rani, V., McKenzie, S. M. and Farrell, A. P.** (2019). Autonomic cardiac  
 303 regulation facilitates acute heat tolerance in rainbow trout: *in situ* and *in vivo*  
 304 support. *J. Exp. Biol.* jeb.194365.
- 305 **Jones, D. R. and Randall, D. J.** (1978). The respiratory and circulatory systems during  
 306 exercise. In *Fish Physiology Volume 7* (ed. Hoar, W. S.) and Randall, D. J.), pp. 1–59.  
 307 New York: Academic Press.

- 308 **Jutfelt, F., Norin, T., Ern, R., Overgaard, J., Wang, T., McKenzie, D. J., Lefevre, S., Nilsson,**  
309 **ran E., Metcalfe, N. B., R Hickey, A. J., et al. (2018).** Oxygen- and capacity-limited  
310 thermal tolerance: blurring ecology and physiology. *J. Exp. Biol.* **221**, 2016–2019.
- 311 **Killen, S. S., Norin, T. and Halsey, L. G. (2017).** Do method and species lifestyle affect  
312 measures of maximum metabolic rate in fishes? *J. Fish Biol.* **90**, 1037–1046.
- 313 **Kir, M. and Demirci, Ö. (2018).** Thermal tolerance and standard metabolic rate of juvenile  
314 European sea bass (*Dicentrarchus labrax*, Linnaeus, 1758) acclimated to four  
315 temperatures. *J. Therm. Biol.* **78**, 209–213.
- 316 **Lefevre, S. (2016).** Are global warming and ocean acidification conspiring against marine  
317 ectotherms? A meta-analysis of the respiratory effects of elevated temperature,  
318 high CO<sub>2</sub> and their interaction. *Conserv. Physiol.* **4**, 1–31.
- 319 **Lefevre, S., Wang, T. and McKenzie, D. J. (2021).** The role of mechanistic physiology in  
320 investigating impacts of global warming on fishes. *J. Exp. Biol.* **224**, jeb238840.
- 321 **Lutterschmidt, W. I. and Hutchison, V. H. (1997).** The critical thermal maximum: history and  
322 critique. *Can. J. Zool.* **75**, 1561–1574.
- 323 **McArley, T. J., Hickey, A. J. R. and Herbert, N. A. (2017).** Chronic warm exposure impairs  
324 growth performance and reduces thermal safety margins in the common triplefin  
325 fish (*Forsterygion lapillum*). *J. Exp. Biol.* **220**, 3527–3535.
- 326 **McArley, T. J., Sandblom, E. and Herbert, N. A. (2021).** Fish and hyperoxia—From  
327 cardiorespiratory and biochemical adjustments to aquaculture and ecophysiology  
328 implications. *Fish Fish.* **22**, 324–355.
- 329 **McKenzie, D. J. and Claireaux, G. (2010).** The effects of environmental factors on the  
330 physiology of aerobic exercise. In *Fish Locomotion: An Eco-ethological Perspective*  
331 (ed. Domenici, P.) and Kapoor, B. G.), pp. 308–344. Boca Raton: CRC Press.
- 332 **Norin, T., Canada, P., Bailey, J. A. and Gamperl, A. K. (2019).** Thermal biology and  
333 swimming performance of Atlantic cod (*Gadus morhua*) and haddock (  
334 *Melanogrammus aeglefinus*). *PeerJ* **7**, e7784.
- 335 **Penney, C. M., Nash, G. W. and Kurt Gamperl, A. (2014).** Cardiorespiratory responses of  
336 seawater-acclimated adult Arctic char (*Salvelinus alpinus*) and Atlantic salmon  
337 (*Salmo salar*) to an acute temperature increase. *Can. J. Fish. Aquat. Sci.* **71**, 1096–  
338 1105.
- 339 **Pörtner, H. O. (2010).** Oxygen- and capacity-limitation of thermal tolerance: A matrix for  
340 integrating climate-related stressor effects in marine ecosystems. *J. Exp. Biol.* **213**,  
341 881–893.
- 342 **Pörtner, H.-O. (2021).** Climate impacts on organisms, ecosystems and human societies:  
343 integrating OCLTT into a wider context. *J. Exp. Biol.* **224**, jeb238360.

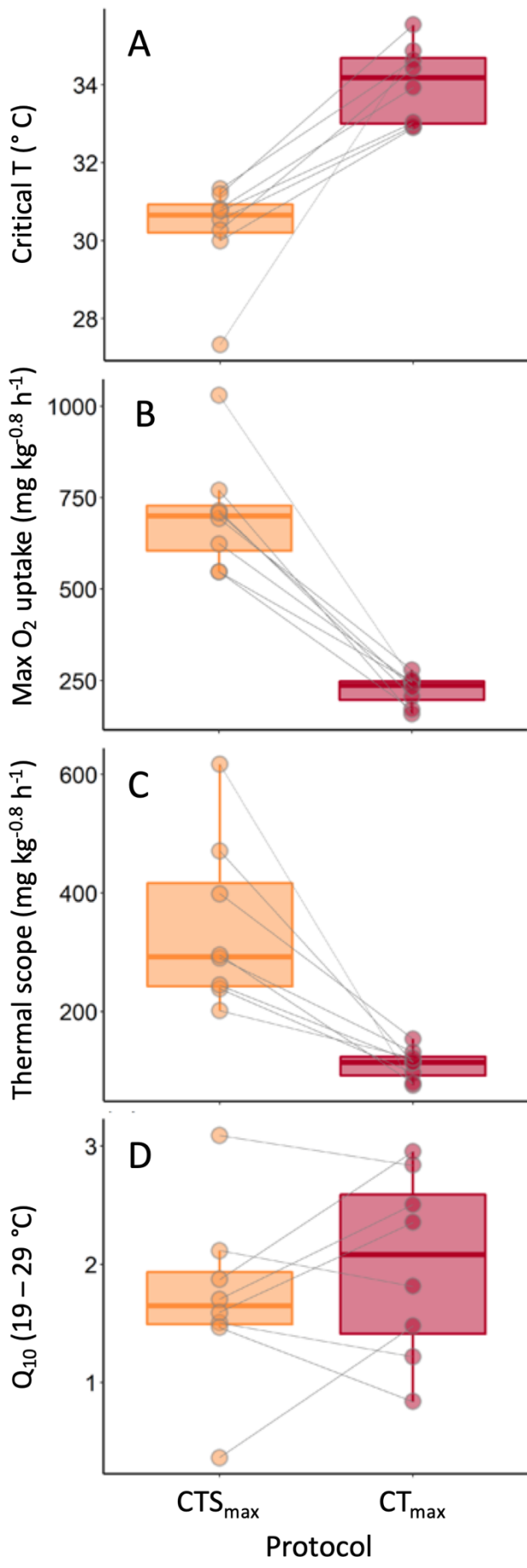
- 344 **Pörtner, H.-O. and Farrell, A. P.** (2008). Physiology and climate change. *Science* **322**, 690–  
345 692.
- 346 **Rezende, E. L., Tejedó, M. and Santos, M.** (2011). Estimating the adaptive potential of  
347 critical thermal limits: methodological problems and evolutionary implications.  
348 *Funct. Ecol.* **25**, 111–121.
- 349 **Rezende, E. L., Castañeda, L. E. and Santos, M.** (2014). Tolerance landscapes in thermal  
350 ecology. *Funct. Ecol.* **28**, 799–809.
- 351 **Rodde, C., de Verdal, H., Vandeputte, M., Allal, F., Nati, J., Besson, M., Blasco, F. R.,  
352 Benzie, J. A. H. and McKenzie, D. J.** (2021). An investigation of links between  
353 metabolic rate and feed efficiency in European sea bass *Dicentrarchus labrax*. *J.*  
354 *Anim. Sci.* **99**,.
- 355 **Schulte, P. M.** (2015). The effects of temperature on aerobic metabolism: Towards a  
356 mechanistic understanding of the responses of ectotherms to a changing  
357 environment. *J. Exp. Biol.* **218**, 1856–1866.
- 358 **Steffensen, J. F.** (1989). Some errors in respirometry of aquatic breathers: How to avoid and  
359 correct for them. *Fish Physiol. Biochem.* **6**, 49–59.
- 360 **Steinhausen, M. F., Sandblom, E., Eliason, E. J., Verhille, C. and Farrell, A. P.** (2008). The  
361 effect of acute temperature increases on the cardiorespiratory performance of  
362 resting and swimming sockeye salmon (*Oncorhynchus nerka*). *J. Exp. Biol.* **211**, 3915–  
363 3926.
- 364 **Vornanen, M.** (2020). Feeling the heat: source–sink mismatch as a mechanism underlying  
365 the failure of thermal tolerance. *J. Exp. Biol.* **223**, jeb225680.
- 366 **Wang, T., Lefevre, S., Iversen, N. K., Findorf, I., Buchanan, R. and McKenzie, D. J.** (2014).  
367 Anaemia only causes a small reduction in the upper critical temperature of sea bass:  
368 is oxygen delivery the limiting factor for tolerance of acute warming in fishes? *J. Exp.*  
369 *Biol.* **217**, 4275–4278.
- 370 **Webb, P. W.** (1998). Swimming. In *The Physiology of Fishes* (ed. Evans, D. D.), pp. 1–38. Boca  
371 Raton: CRC Press.
- 372

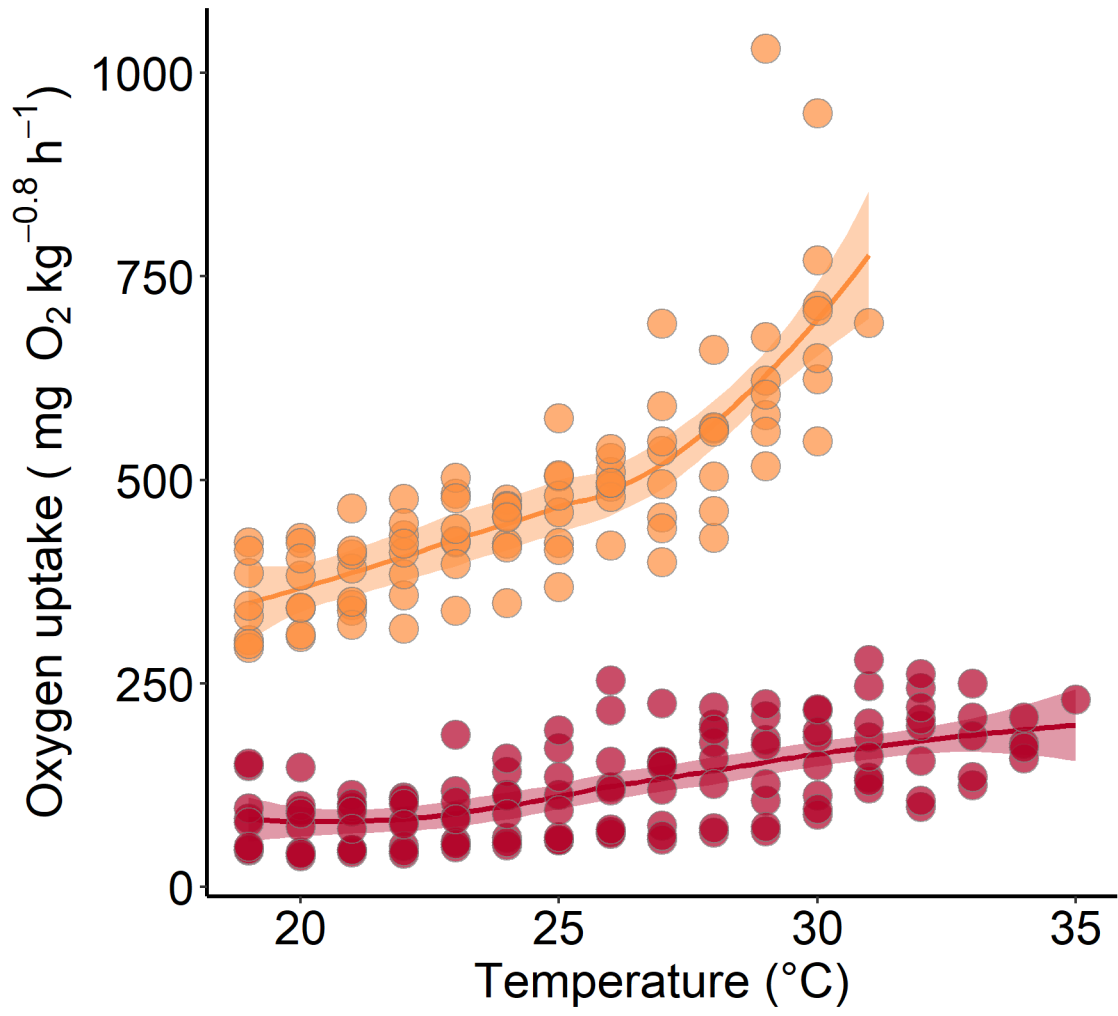
373 **Figure legends**

374 Figure 1. Boxplots of data for critical temperature of endpoint (A); maximum rate of oxygen  
375 uptake achieved (B); thermal scope, calculated as maximum rate of oxygen uptake minus  
376 rate at 19 °C (C), and Q10 for effects of temperature on oxygen uptake between 19 °C and  
377 29 °C (D). Two thermal ramping protocols are compared in n = 8 European seabass, either  
378 critical thermal maximum for swimming ( $CTS_{max}$ ) exercising aerobic with fatigue as endpoint,  
379 or critical thermal maximum ( $CT_{max}$ ) under static conditions with loss of equilibrium as  
380 endpoint. Each point is an individual, the lines connecting the two protocols show how that  
381 individual responded to each. Boxplot lower and upper hinges represent the 25<sup>th</sup> and 75<sup>th</sup>  
382 percentiles. The horizontal line within the box is the median. The length of whiskers  
383 represents the range of data points between each hinge and 1.5× the difference between  
384 the 25<sup>th</sup> and 75<sup>th</sup> percentiles. Data beyond these limits are outliers.

385 Figure 2. Rate of oxygen uptake in n = 8 European seabass during exposure to two thermal  
386 ramping protocols, either critical thermal maximum for swimming ( $CTS_{max}$ ) exercising  
387 aerobic with fatigue as endpoint (19 °C to 31 °C, orange symbols and curve), or critical  
388 thermal maximum ( $CT_{max}$ ) under static conditions with loss of equilibrium as endpoint (19 to  
389 35°C, red symbols and curve). Each point represents an individual, the temperature ranges  
390 are those for which oxygen uptake data was collected on all individuals, the shaded area  
391 shows the 95% confidence interval.

392





394