



**HAL**  
open science

## The relationship between membrane fatty acid content and mitochondrial efficiency differs within- and between-omega-3 dietary treatments

Karine Salin, Margaux Mathieu-Resuge, Nicolas Graziano, Emmanuel Dubillot, Fabienne Le Grand, Philippe Soudant, Marie Vagner

### ► To cite this version:

Karine Salin, Margaux Mathieu-Resuge, Nicolas Graziano, Emmanuel Dubillot, Fabienne Le Grand, et al.. The relationship between membrane fatty acid content and mitochondrial efficiency differs within- and between- omega-3 dietary treatments. *Marine Environmental Research*, 2020, 163, pp.105205. 10.1016/j.marenvres.2020.105205 . hal-02409224

**HAL Id: hal-02409224**

**<https://hal.science/hal-02409224v1>**

Submitted on 22 Aug 2024

**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.

1 **TITLE:** The relationship between membrane fatty acid content and mitochondrial efficiency differs  
2 within- and between- omega-3 dietary treatments

3

4 **AUTHORS:**

5 Karine Salin<sup>1\*</sup>, Margaux Mathieu-Resuge<sup>2</sup>, Nicolas Graziano<sup>1,3</sup>, Emmanuel Dubillot<sup>3</sup>, Fabienne Le  
6 Grand<sup>1</sup>, Philippe Soudant<sup>1</sup>, Marie Vagner<sup>1,3</sup>

7

8 **AFFILIATIONS:**

9 <sup>1</sup> Univ Brest, Ifremer, CNRS, IRD, LEMAR, F-29280, Plouzané, France

10 <sup>2</sup> WasserCluster Lunz — Inter-University Centre for Aquatic Ecosystem Research, Dr. Carl Kupelwieser  
11 Promenade 5 A-3293 Lunz am See, Austria

12 <sup>3</sup> UMR 7266 LIENSs, 2 rue Olympe de Gouges 17000 La Rochelle, France

13

14 **\*CORRESPONDING AUTHOR:** Karine Salin; Email: [Karine.salin@ifremer.fr](mailto:Karine.salin@ifremer.fr)

15

16 **RUNNING TITLE:** n-3 HUFA levels alter mitochondrial efficiency

17

18 **KEYWORDS:** ATP/O ratio, docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), food quality,  
19 *Chelon auratus*, global change.

20 **ABSTRACT**

21 An important, but underappreciated, consequence of climate change is the reduction in  
22 crucial nutrient production at the base of the marine food chain: the long-chain omega-3 highly  
23 unsaturated fatty acids (n-3 HUFA). This can have dramatic consequences on consumers, such as fish  
24 as they have limited capacity to synthesise n-3 HUFA *de novo*. The n-3 HUFA, such as  
25 docosahexaenoic acid (DHA, 22:6n-3) and eicosapentaenoic acid (EPA, 20:5n-3), are critical for the  
26 structure and function of all biological membranes. There is increasing evidence that fish will be  
27 badly affected by reductions in n-3 HUFA dietary availability, however the underlying mechanisms  
28 remain obscure. Hypotheses for how mitochondrial function should change with dietary n-3 HUFA  
29 availability have generally ignored ATP production, despite its importance to a cell's total energetics  
30 capacity, and in turn, whole-animal performance. Here we (i) quantified individual variation in  
31 mitochondrial efficiency (ATP/O ratio) of muscle and (ii) examined its relationship with content in  
32 EPA and DHA in muscle membrane of a primary consumer fish, the golden grey mullet *Chelon*  
33 *auratus*, receiving either a high or low n-3 HUFA diet. Mitochondria of fish fed on the low n-3 HUFA  
34 diet had higher ATP/O ratio than those of fish maintained on the high n-3 HUFA diet. Yet,  
35 mitochondrial efficiency varied up about 2-fold among individuals on the same dietary treatment,  
36 resulting in some fish consuming half the oxygen and energy substrate to produce the similar amount  
37 of ATP than conspecific on similar diet. This variation in mitochondrial efficiency among individuals  
38 from the same diet treatment was related to individual differences in fatty acid composition of the  
39 membranes: a high ATP/O ratio was associated with a high content in EPA and DHA in biological  
40 membranes. Our results highlight the existence of interindividual differences in mitochondrial  
41 efficiency and its potential importance in explaining intraspecific variation in response to food chain  
42 changes.

## 43 1. Introduction

44 Fish provide critical sustenance for millions of people worldwide and have far reaching impacts on  
45 the productivity of ecosystems (McIntyre et al., 2016). Yet, ongoing and future climate change  
46 threatens the persistence of fish populations globally (Pörtner and Knust, 2007). An important, but  
47 underappreciated, consequence of climate change is the reduction in production at the base of the  
48 food chain of essential nutrient: the long-chain omega-3 highly unsaturated fatty acids (n-3 HUFA)  
49 (da Motta Pacheco et al., 2014; Galloway and Winder, 2015; Hixson and Arts, 2016). **Water warming**  
50 **(Hixson and Arts, 2016), acidification (Bermudez et al., 2015), or UV irradiation (Kang, 2011), all affect**  
51 **n-3 HUFA primary producers physiology and community assemblages, leading to a dominance of n-3**  
52 **HUFA-impooverished taxa (Galloway and Winder, 2015).** The n-3 HUFA such as eicosapentaenoic acid  
53 (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3) are essential to the structure and function  
54 of all biological membranes and are thus considered to be important drivers of organism  
55 performance (Hulbert et al., 2005; Ishizaki et al., 2001; Mazorra et al., 2003; Vagner et al., 2015).  
56 Endogenous biosynthesis of n-3 HUFA from precursors is limited in most vertebrates, including  
57 marine fish (Alimuddin et al., 2005; Arts and Kohler, 2009; Oboh et al., 2017). Changes in the n-3  
58 HUFA availability in the fish diet causes strongly correlated changes in the fatty acid composition of  
59 their biological membranes (Guderley et al., 2008; Nogueira et al., 2001; Ramsey et al., 2005). Fish on  
60 n-3 HUFA-deficient diets can perform badly: reductions in EPA and DHA dietary content **reduced**  
61 **growth (Norambuena et al., 2015; Vagner et al., 2015) and thermal tolerance (Vagner et al., 2014),**  
62 **and altered whole-organism metabolic traits (Vagner et al., 2015; Vagner et al., 2014).** Determining  
63 what causes animal performance to vary with n-3 HUFA diet constitutes a fundamental step in  
64 predicting the impacts of projected oceanic changes on fish resilience (Kang, 2011).

65 Consideration of mitochondrial capacity to make ATP may improve our understanding of the  
66 links between dietary n-3 HUFA availability and whole-animal performance. Mitochondrial ATP is  
67 produced via oxidative phosphorylation, a process through which energy substrates are oxidized to  
68 generate a protonmotive force that drives the phosphorylation of ADP to ATP. Hypotheses for how  
69 mitochondrial function should change with dietary n-3 HUFA availability have focused on variation in  
70 respiratory capacities and have generally ignored variation in ATP production (Kraffe et al., 2007;  
71 Ramsey et al., 2005; but see Herbst, 2014; Vagner et al., 2015; Vagner et al., 2014). Although ATP  
72 production depends on the rate of substrate oxidation, the number of ATP molecules produced for  
73 each atom of oxygen consumed by the mitochondria during substrate oxidation (ATP/O ratio) can  
74 vary (Brand, 2005; Salin et al., 2015). A fraction of the protonmotive force that is generated from  
75 substrate oxidation is dissipated through proton leak across mitochondrial inner membranes and this  
76 leakage can decrease the protonmotive force available to produce ATP (Brand, 2005; Kadenbach,  
77 2003). Thus, the **greater** the mitochondria leak, the less efficiently an animal converts its metabolic

78 substrates into ATP, and the **lower** the ATP/O ratio. The proportion of energy dissipated in the  
79 proton leak and the efficiency to make ATP vary among conspecific (Bottje and Carstens, 2009;  
80 Robert and Bronikowski, 2010; Salin et al., 2016b) and can be influenced by environmental factors  
81 including diet (Fontaine et al., 1996; Salin et al., 2018). A number of studies have found positive links  
82 between intraspecific heterogeneity in efficiency to produce mitochondrial ATP and the whole-  
83 organism performance, such as locomotory performance (Coen et al., 2012; Distefano et al., 2018;  
84 but see Jahn and Seebacher, 2019), developmental rate (Salin et al., 2012), growth efficiency (Bottje  
85 and Carstens, 2009; Salin et al., 2019) and reproductive output (Robert and Bronikowski, 2010),  
86 suggesting that it might be a trait of ecological relevance.

87         Recent research has recognized the importance of accounting for individual heterogeneity in  
88 predicting responses to global changes (Hamel et al., 2018). Because some individuals perform much  
89 better than others **within** the same environment, individual heterogeneity is likely to directly  
90 influence the potential for species to evolve adaptations for a reduced n-3 HUFA availability. A  
91 number of studies have found positive links between n-3 HUFA content in membranes and  
92 mitochondrial proton leak when comparing among species (Brand et al., 1994; Brookes et al., 1998),  
93 but contradictory results were found when comparing treatment groups with studies reporting  
94 positive (Martin et al., 2013), negative (Fontaine et al., 1996; Guderley et al., 2008) or no  
95 relationships (Guderley et al., 2008) between content in n-3 HUFA in mitochondrial membranes and  
96 leak respiration. N-3 HUFA are thought to have important effects on the mitochondrial capacity to  
97 make ATP; but until now, there has, to our knowledge, been no assessment of whether membrane n-  
98 3 HUFA content could explain variation in mitochondrial metabolism among individuals.

99         The present experiment integrates measurements of mitochondrial efficiency and  
100 mitochondrial proton leak to determine whether reductions in EPA and DHA availability in food led to  
101 changes in energy metabolism of a primary consumer fish. We first examined the effect of dietary n-  
102 3 HUFA content on mitochondrial function, in particular on the efficiency to produce ATP (ATP/O  
103 ratio) and the respiratory capacities to offset the proton leak (LEAK respiration). Secondly, we tested  
104 whether differences between individuals in mitochondrial efficiency and mitochondrial LEAK  
105 respiration vary with membrane n-3 HUFA content. To address this, we experimentally manipulated  
106 the quantity of n-3 HUFA in food for wild-caught juvenile golden grey mullet (*Chelon auratus*). Fish  
107 were fed either a high n-3 HUFA or low n-3 HUFA **diet**, and their membrane fatty acid composition  
108 and mitochondrial functioning were determined in skeletal muscle. We choose juvenile golden grey  
109 mullet as our study organism because they are likely to be the first levels of the food chain to face a  
110 decline in availability of dietary n-3 HUFA, as this fish fed mainly on primary producers (Lebreton et  
111 al., 2011; Mourente and Tocher, 1993). We analysed mitochondrial properties in the skeletal muscle  
112 because the mitochondrial function of this tissue is known to influence whole-animal performance

113 (Coen et al., 2012; Salin et al., 2016a), and that fatty acid dietary content influences muscle  
114 membrane fatty acid composition (McKenzie et al., 1998; Vagner et al., 2015).

115

## 116 **2. Materiel and methods**

### 117 *2.1. Fish origin and care*

118 Wild juvenile golden grey mullets (n = 23) were netted from the marshes of L'Houmeau France  
119 (46°12'14.4"N 1°11'43.7"W) in November 2017 and transported to the laboratory Littoral  
120 Environment Society (LIENSs), France, where all the experiments were conducted. Fish were kept in a  
121 common thermoregulated 300 L-tank supplied with aerated recirculated sand-filtered natural  
122 seawater and equipped with an external biological filter (Eheim, Deizisau, Germany). Fish were  
123 maintained under a 12 L : 12 D photoperiod, and fed daily with commercial pellets (Le Gouessant®,  
124 Lamballe, France). Temperature ( $13.8 \pm 0.2^\circ\text{C}$ ) and salinity ( $28.7 \pm 0.1$ ) were monitored daily  
125 (TetraCon® 325, Laboratoires Humeau, La Chapelle-sur-Erdre, France) and were kept similar to that  
126 of the sampling site. Oxygen ( $87.9 \pm 2.6\%$  air saturation) was monitored once a week. Fish were  
127 acclimated for seven weeks to these conditions. The collection and handling of the animals were  
128 carried out under the jurisdiction of the Departmental Service of Fisheries and the Animal Care  
129 Committee of France (# 12886), respectively.

130 In January 2018, fish were anesthetized in  $0.1 \text{ g L}^{-1}$  MS-222 (Ethyl 3-aminobenzoate  
131 methanesulfonate) in seawater, measured for body mass ( $34.3 \pm 6.5 \text{ g}$ ), individually pit-tagged  
132 (Biolog-id, Bernay, France), and randomly assigned to one of the four replicate 300-L holding tanks  
133 (n=5-6 fish per tank). All fish were fasted for 24h beforehand to ensure their guts were empty. Fish  
134 were acclimated for 4 weeks in their new tanks, during which time they were fed commercial pellets  
135 twice daily to a total of 2% of their biomass (Le Gouessant®, Lamballe, France).

136 In February 2018, fish were gradually acclimated to  $20^\circ\text{C}$  by means of a sequence of 3 step  
137 increases of  $2^\circ\text{C}$  over a two-week period. This temperature was chosen because it is the temperature  
138 at which whole-organism performance declined in mullet fed on a low n-3 HUFA diet, but is within  
139 their natural thermal range as  $20^\circ\text{C}$  reflects the mean summer temperature in mullet natural  
140 environment (Vagner et al., 2015; Vagner et al., 2014). Fish were left another 2 weeks period of  
141 acclimation to initiate physiological adjustment to the change in temperature (Bouchard and  
142 Guderley, 2003). Temperature ( $19.9 \pm 1^\circ\text{C}$ ) and salinity ( $29.6 \pm 1.1$ ) were daily measured in the four  
143 experimental tanks.

144

### 145 *2.2. Diet treatment and tissue sampling*

146 Differences in dietary n-3 HUFA content were achieved by replacing fish oil (rich in n-3 HUFA) of the  
147 High n-3 HUFA diet with rapeseed oil (poor in n-3 HUFA) in the Low n-3 HUFA diet (See ingredients in

148 Table S1 (a)). Experimental diets were isocaloric and isolipidic. High and Low n-3 HUFA diets  
149 contained 17.5 % and 1.2 % EPA+DHA, respectively, per total fatty acid mass of the diets, which  
150 represents about 15-fold difference in EPA and DHA content between diets (See Table S1 (a) for fatty  
151 acid composition of the diets). The EPA and DHA content in High n-3 HUFA diet cover the needs of  
152 several fish species (Robin and Skalli, 2007), **although** the needs of the golden grey mullet are not  
153 known. The Low n-3 HUFA diet was estimated to significantly reduce n-3 HUFA content in biological  
154 membranes and has been shown to impair aerobic performance of golden grey mullet at 20°C  
155 (Vagner et al., 2015).

156 Following the period of acclimation to water temperature of 20°C, fish were switched to the  
157 experimental diets for about two months (mean  $\pm$  SEM =  $61 \pm 2$  days, range: 45 – 73 days). This  
158 duration was chosen because it is sufficient to detect differences in the membrane fatty acid  
159 composition between diet treatments (Robin and Skalli, 2007). Because only two fish per day could  
160 be analysed for their mitochondrial function at the end of the experiment, the duration of the diet  
161 treatment differed between processing batches. Fish were randomly allocated to the treatment: fish  
162 had their food progressively switched to either the High n-3 HUFA diet (n = 11) or the Low n-3 HUFA  
163 diet (n = 12). The experimental diet to commercial diet ratio was increased every second day from  
164 25%:75% to 50%:50%, 75%:25% and finally to 100%:0%. Body mass did not differ between fish  
165 groups subsequently assigned to the two food treatments (High n-3 HUFA diet:  $31.3 \pm 1.8$  g; Low n-3  
166 HUFA diet:  $34.9 \pm 1.5$  g, *t*-test:  $t_{21} = -1.510$ , *p* = 0.146). Body mass was re-measured (as above) every  
167 2-3 weeks and rations were recalculated to adjust for growth.

168 At the end of the food treatment period, fish were fasted for 24 h before being anesthetized  
169 and culled. Fish were weighed, measured and two samples of skeletal muscle were immediately  
170 dissected, taken dorsally from the lateral line (to have both red and white muscle) and just behind  
171 the head. One aliquot was collected from one side of the fish and kept in ice-cold isolation buffer  
172 (sucrose 250 mM, EGTA 1mM, Tris-HCl 20mM, pH 7.4 at 4°C) for immediate mitochondrial assay,  
173 while the other aliquot ( $\approx 1$  g) was collected from the other side and immediately flash-frozen for  
174 subsequent fatty acid analysis.

175

### 176 2.3. Determination of fatty acid composition

#### 177 2.3.1. Lipid extraction

178 Lipids from muscle of fish were extracted following the method used in Mathieu-Resuge et al. (2019).  
179 Muscle aliquots were ground into a fine homogeneous powder in liquid nitrogen. Lipids from 200-  
180 250 mg of muscle powder were then extracted in 6 ml of mixture chloroform/methanol (2:1; v/v). To  
181 ensure complete lipid extraction, samples were sonicated at 4 °C during 2 x 5 min. Lipids from  
182 experimental diets were extracted following the same method. Pellets were ground in a mortar and

183 powder was transferred in chloroform/methanol (2:1; v/v). All lipid extracts were then stored at -20  
184 °C under nitrogen atmosphere until further analysis.

185

### 186 *2.3.2. Purification of polar lipids*

187 Fatty acids of biological membranes are connected to a polar head group, altogether named polar  
188 lipid (PL), unlike fatty acids of energy stores that constitute triglyceride, a neutral lipid. To analyse the  
189 FA composition of biological membrane, PL were separated from neutral FA and FA from only PL  
190 were considered. PL were separated from neutral one by solid-phase extraction following the  
191 method described in (Martin et al., 2013). Briefly, an aliquot of muscle total lipid extract (1/6) was  
192 evaporated to dryness under nitrogen, recovered with 3 washings of 0.5 ml of chloroform/methanol  
193 (98:2; v/v) and deposited at the top of a silica gel column (40 mm × 4 mm, silica gel 60A 63–200 µm)  
194 previously heated at 450°C and deactivated with 6 weight % H<sub>2</sub>O. After elution of neutral lipids with  
195 10 mL of chloroform/methanol (98:2; v/v), PL were eluted with 20 mL of methanol, transferred into a  
196 vial containing 2.3 µg of internal standard (tricosanoic acid C23:0) and stored at -20°C under nitrogen  
197 atmosphere.

198

### 199 *2.3.3. Polar lipid transesterification*

200 Polar lipid transesterification was realized as described in Mathieu-Resuge et al. (2019). PL fractions  
201 were evaporated to dryness under nitrogen. Fatty acid methyl esters (FAME) were obtained by  
202 addition of 800 µL of H<sub>2</sub>SO<sub>4</sub> / methanol (3.4 %; v/v) and heating at 100°C for 10 min. FAME were then  
203 extracted in 800 µL of hexane and washed three times with 1.5 ml of distilled water saturated in  
204 hexane.

205

### 206 *2.3.4. Gas chromatography analysis of FAME*

207 FA composition was analysed by GC coupled with Flame-Ionization Detector (GC-FID) as described by  
208 Mathieu-Resuge et al. (2019) with a Varian CP8400 gas chromatograph. After splitless-mode  
209 injection, FAME were separated in parallel on two different columns (DBWAX 30 m × 0.25 mm ID x  
210 0.2 µm and DB5 30 m × 0.25 mm ID x 0.2 µm, Agilent). FAME were identified by comparisons of their  
211 retention time with those of commercial standards (Supelco 37 Component FAME Mix, PUFA No.1  
212 and No.3, and Bacterial Acid Methyl Ester Mix, Sigma) and lab-made standard mixtures. The internal  
213 standard (C23:0) allowed to calculate the FA content (µg mg<sup>-1</sup> muscle wet mass). Fatty acid content  
214 was then determined as the percentage of fatty acid mass per total mass of fatty acids in membrane  
215 lipids from the polar lipids fraction. The sum of EPA and DHA content in membrane lipids was  
216 calculated as:



$$\Sigma \text{ EPA + DHA content} = \frac{\text{mass of EPA} + \text{mass of DHA}}{\text{total mass of fatty acids}} \times 100$$

217

## 218 2.4. Mitochondrial function

### 219 2.4.1. Isolation of mitochondria

220 Isolation of muscle mitochondria and measurement of mitochondrial efficiency were adjusted from  
221 published protocols (Ghanizadeh Kazerouni et al., 2016; Salin et al., 2016c). Briefly, mitochondria  
222 were isolated from 1 g (mean  $\pm$  SEM: 1.07  $\pm$  0.03 g) of muscle. Tissue was finely chopped on ice and  
223 homogenized in 10 mL of isolation buffer by four gentle passes in a Potter-Elvehjem homogenizer  
224 and centrifuged at 500 g for 5 min at 4°C. The supernatant was transferred in a clean tube and  
225 centrifuged at 1000 g for 5 min at 4°C and then centrifuged at 9000 g for 10 min at 4°C. The pellet  
226 containing mitochondria was gently resuspended in 500  $\mu$ L assay buffer at 4°C (20mM Taurine,  
227 10mM KH<sub>2</sub>PO<sub>4</sub>, 20 mM HEPES, 110 mM D-sucrose, 60 mM K-lactobionate, 1g L<sup>-1</sup> BSA fatty acid free,  
228 pH 7.2 at 20°C).

229

### 230 2.4.2 Mitochondrial ATP/O ratio and LEAK respiration measurements

231 Mitochondrial efficiency has been quantified through the measurement of the ATP/O ratio, which is  
232 the amount of ATP generated per unit of oxygen consumed. Mitochondrial LEAK respiration was  
233 determined as the rate of oxygen consumption when ATP synthesis was inhibited. We used a  
234 protocol that simultaneously measures both mitochondrial ATP production and the oxygen  
235 consumption related to that ATP production, as in Salin et al. (2016c). Assays were conducted at  
236 20°C.

237 Oxygen and magnesium green fluorescence signals were detected simultaneously using two  
238 respirometry chambers equipped with fluorescent sensors and recorded using DatLab software  
239 (Oroboros Instruments, Innsbruck Austria). To estimate ATP production we used the magnesium-  
240 sensitive fluorescent probe, Magnesium Green, to determine changes in [Mg<sup>2+</sup>] (Szmackinski and  
241 Lakowicz, 1996). ATP production was then calculated from the rate of change in [Mg<sup>2+</sup>] and is based  
242 on the unequal affinities of ATP and ADP for Mg<sup>2+</sup> (Chinopoulos et al., 2009).

243 The oxygen electrodes were calibrated at two points: air-saturated assay buffer (daily) and  
244 zero oxygen after sodium dithionite addition (fortnightly). Stepwise additions of MgCl<sub>2</sub> at each run  
245 were performed for calibration of the fluorescent signal into Mg<sup>2+</sup>. The two binding affinity (K<sub>d</sub>)  
246 values of ATP and ADP for Mg<sup>2+</sup> were determined in presence of isolated mitochondria and calculated  
247 as in (Chinopoulos et al., 2014) ; the values were K<sub>d-ATP</sub> = 0.197 mM and K<sub>d-ADP</sub> = 1.609 mM.

248 Isolated mitochondria from each fish were added to one of the two measurement chambers  
249 of the oxygraph immediately following isolation; fish from a processing pair (i.e. a Low and a High n-3  
250 HUFA) were measured in parallel. The remaining part of the isolated mitochondria was preserved on

251 ice for use in a replicate trial. Assays contained 200  $\mu\text{l}$  of isolated mitochondria with 1.8 mL of assay  
252 buffer in the presence of complex I substrates (5 mM pyruvate and 0.5 mM malate) and complex II  
253 substrate (10 mM succinate). Magnesium green (2.2  $\mu\text{M}$ ), EGTA (0.1 mM), EDTA (5  $\mu\text{M}$ ) and  $\text{MgCl}_2$  (1  
254 mM) were added to determine changes in  $[\text{Mg}^{2+}]$  and so to calculate the rate of ATP production as in  
255 (Chinopoulos et al., 2014).

256 The rate of oxygen consumption to support ATP production was assessed by adding a  
257 saturating concentration of ADP (2 mM,  $\text{Mg}^{2+}$  free) to the chamber. The raw rate of ATP production  
258 was also measured in this condition. The rate of oxygen consumption to offset the leakage of proton  
259 – LEAK respiration - was then measured after inhibition of mitochondrial ATP synthesis (with 4  $\mu\text{M}$   
260 carboxyatractyloside). The rate of ATP hydrolysis was also measured in this condition. The rate of  
261 ATP hydrolysis was then added to the raw rate of ATP production to obtain the corrected rate of ATP  
262 production. Addition of complex I inhibitor (0.5  $\mu\text{M}$  rotenone) and complex III inhibitor (2.5  $\mu\text{M}$   
263 antimycin A) allowed determination of residual oxygen consumption, which was then subtracted  
264 from all other oxygen consumption values. The second replicated trial was used to control for  
265 repeatability of the assay. It was identical to the first one, but started an hour and half later, using  
266 the remaining isolated mitochondrial and the same measurement chamber. Every second day, the  
267 measurement chamber associated with a treatment group was reversed to control for any inter-  
268 respirometry chamber difference in readings. No effect of the choice of measurement chamber on  
269 mitochondrial function was detected.

270

#### 271 2.4.3. Analysis of Mitochondrial ATP/O ratio and LEAK respiration

272 We expressed respiration rate as pmoles of  $\text{O}_2 \text{ sec}^{-1} \text{ ml}^{-1}$  of assay buffer and ATP production  
273 as pmoles of  $\text{ATP sec}^{-1} \text{ ml}^{-1}$  of assay buffer for each replicate. Finally, the ATP/O ratio was calculated  
274 as the ratio of corrected ATP production to two-fold respiration that supported ATP production; the  
275 rate of respiration is doubled since each molecule of oxygen is comprised of two oxygen atoms.  
276 Replicated ATP/O ratios were highly correlated (Pearson's  $r = 0.749$ ,  $P < 0.001$ ). However, we found a  
277 consistent shift in the values of the measurements between the first and the second trials of ATP/O  
278 ratio (drift between trials: Paired  $t = -6.194$ ,  $P < 0.001$ ). The data from the second trial of muscle  
279 assay were excluded because the mitochondrial integrity may have been impaired with time post-  
280 isolation, as previously found in liver mitochondria (Salin et al., 2016c). Only data of the first LEAK  
281 respiration and ATP/O ratio trial were kept for the main analyses. Protein concentration was  
282 measured at 595 nm using the Bradford method with bovine serum albumin as a standard. We  
283 expressed LEAK respiration as pmoles of  $\text{O}_2 \text{ sec}^{-1} \text{ mg}^{-1}$  of mitochondrial protein. See descriptive  
284 statistics of the mitochondrial function in Table S2.

285

## 286 2.5. Statistical analysis

287 We first examined the effect of the treatments (High and Low dietary n-3 HUFA content) on  
288 the membrane fatty acid composition ( $\Sigma$  EPA + DHA content). Normality (Shapiro-Wilk test) and  
289 homoscedasticity (Bartlett-test) were tested. When normality and homoscedasticity were not  
290 satisfied, non-parametric analyses were carried out. We used Wilcoxon tests to determine whether  
291 muscle membrane content of EPA and DHA, and their sum ( $\Sigma$  EPA + DHA content) differed between  
292 dietary treatment groups. To examine potential differences in final body mass between treatments  
293 that could explain differences in mitochondrial function, a *t*-test was employed. The effect of the  
294 dietary treatment on mitochondrial function (ATP/O ratio and LEAK respiration) were also analysed  
295 using *t*-tests.

296 We then used linear model **analyses** to test whether ATP/O ratio and LEAK respiration were  
297 correlated with membrane lipid content in  $\Sigma$  EPA + DHA. The models included mitochondrial function  
298 (ATP/O or LEAK respiration) as the dependant variable, dietary treatments as a categorical effect, and  
299  $\Sigma$  EPA + DHA content as continuous predictor. The normality of the linear model residuals was  
300 validated for all models using Shapiro–Wilk tests. We also tested the interactions between dietary  
301 treatment and membrane lipid content in  $\Sigma$  EPA + DHA. All interactions were non-significant, so they  
302 were removed from the models.

303 The duration of the dietary treatment **was included as potential covariate**, the processing  
304 batch and fish tanks were included as potential **random factor** in **initial analysis**. **Each of these**  
305 **variable** were not significant, so were removed from all the **final models**. All statistical analyses were  
306 performed with the free software R (R Core Team, 2017), with R Version 3.6.1, with significance level  
307 set to  $p < 0.05$ . Data are presented as means  $\pm$  standard error of the mean (SEM).

308

## 309 3. Results

### 310 3.1. Effect of the dietary treatment on membrane fatty acid composition

311 Muscle of mullets fed on Low n-3 HUFA diet showed significant differences in their membrane  
312 fatty acid composition compared to those of fish fed on High n-3 HUFA diet (Table S3). EPA and DHA  
313 content in muscle membranes were significantly lower in Low n-3 HUFA fish compared to High n-3  
314 HUFA fish (EPA:  $W = 119$ ,  $p < 0.001$ ; DHA:  $W = 132$ ,  $p < 0.001$ ; Table 1). Not surprisingly, fish on  
315 average had a lower content of  $\Sigma$  EPA+ DHA in their muscle when fed the Low n-3 HUFA diet ( $W =$   
316  $130$ ,  $p < 0.001$ , Table 1). Final body mass did not differ between High and Low n-3 HUFA fish ( $t = -$   
317  $1.668$ ;  $p = 0.112$ ), excluding body mass as confounding sources of differences between dietary  
318 treatments.

319

### 320 3.2. Effect of the dietary treatment on mitochondrial function

321 ATP/O ratio was significantly higher in the mitochondria of Low compared to High n-3 HUFA  
322 mullet ( $t = -3.107$ ,  $p = 0.005$ ; Fig. 1A). However, there was no effect of dietary n-3 HUFA content on  
323 LEAK respiration in muscle mitochondria ( $t = -0.423$ ,  $p = 0.677$ ; Fig. 1B).

324

### 325 *3.3. Relationships across individuals between mitochondrial function and membrane fatty acid* 326 *composition*

327 The ATP/O ratio ranged from 1.46 to 3.33 for mitochondria of mullet eating the High n-3  
328 HUFA diet and from 2.05 to 3.67 for mitochondria of fish on Low n-3 HUFA diet (Fig. 2A). **Variation in**  
329 **mitochondrial function between individuals was mainly explained by differences in n-3 HUFA content**  
330 **in muscle (Figure S1)**. Regardless of the food treatment, the muscle ATP/O ratio of a fish was strongly  
331 and positively related to its  $\Sigma$  EPA + DHA content: individuals that had the higher mitochondrial  
332 efficiency under either diet had the highest content in EPA and DHA in their membranes ( $t = 2.513$ ,  $p$   
333  $= 0.021$ ; Fig. 2A and Table 2). There was no relationship between a fish's mitochondrial LEAK  
334 respiration and its  $\Sigma$  EPA + DHA content among individuals with the same dietary treatment ( $t = -$   
335  $0.104$ ,  $p = 0.919$ , Fig. 2B and Table 2). We found no correlation between ATP/O ratio and LEAK  
336 respiration from the same mitochondria (High n-3 HUFA diet: Pearson's  $r = 0.229$ ,  $p = 0.499$ ; Low n-3  
337 HUFA diet: Pearson's  $r = -0.157$ ,  $p = 0.627$ ).

338

## 339 **4. Discussion**

340 We asked whether a decline in dietary n-3 HUFA content leads to changes in mitochondrial  
341 metabolic phenotype for a model of primary consumer fish, the golden grey mullet. We manipulated  
342 dietary content in n-3 HUFA and assessed membrane FA composition and mitochondrial function in  
343 mullet. We found that diet strongly influenced membrane fatty acid composition: mullets on a Low  
344 n-3 HUFA diet had lower levels of n-3 HUFA in muscle biological membranes, which suggested that  
345 the mitochondrial membranes contained less n-3 HUFA. Previous studies have indeed demonstrated  
346 that modification of the fatty acid composition of the diet causes strongly correlated changes in the  
347 membrane fatty acid composition of mitochondria (Herbst et al., 2014; Jeromson and Hunter, 2014;  
348 Ramsey et al., 2005), including those of fish species (Guderley et al., 2008; Morash et al., 2009). Our  
349 findings reveal that ATP/O ratio increased significantly in mitochondria of fish fed a low n-3 HUFA  
350 diet, so that a decline in dietary content in n-3 HUFA elicits greater mitochondrial efficiency to  
351 produce ATP. **Surprisingly, the differences in membrane n-3 HUFA content between individuals had**  
352 **an opposite effect on mitochondrial efficiency**: under the same dietary treatment, **individuals** that  
353 displayed higher EPA and DHA **membrane content** had mitochondria with the highest ATP/O ratio.

354 Aerobic performance of marine fish will not only be challenged in a near future by increased  
355 oxygen needs and low oxygen availability at high temperatures but probably also by a shift in ocean

356 productivity (Behrenfeld et al., 2006), where EPA and DHA availability might decline considerably  
357 (Hixson and Arts, 2016). Mitochondrial aerobic capacity has traditionally been determined in terms  
358 of oxygen consumption, enzymatic activities or density of mitochondria (Brookes et al., 1998;  
359 Guderley et al., 2008; Martin et al., 2013; Morash et al., 2009; Ramsey et al., 2005; Yu et al., 2014).  
360 However, oxygen consumption provides only an indirect measure of ATP production, and the  
361 relationship between oxygen consumption and ATP production can vary both among and within  
362 individuals. Our results clearly show that when evaluating mitochondrial adjustment in response to a  
363 reduction in n-3 HUFA availability in diet, variation in the amount of ATP generated per molecule of  
364 oxygen consumed by mitochondria can have major importance in explaining associated changes in  
365 whole-animal performance. Past work on mullets found that fish fed on a low n-3 HUFA diet  
366 consumed less oxygen compared to the fish fed a high n-3 diet to reach a similar swimming speed  
367 (Vagner et al., 2015; Vagner et al., 2014). Our results suggest that higher mitochondrial efficiency  
368 may result in lower oxygen requirement for fish to produce ATP and sustain muscle contraction for  
369 locomotory performance, as previously demonstrated in human (Coen et al., 2012). Mitochondria  
370 with high efficiency can be beneficial for energy-demanding cellular processes (Salin et al., 2015), yet  
371 there could also be a cost. Mitochondria are a major producer of reactive oxygen species (ROS) and  
372 mitochondrial efficiency can be positively related to ROS production (Brand, 2000; Salin et al., 2015),  
373 an area which would require further study.

374 Here, we found no significant differences in LEAK respiration of mullet muscle across dietary  
375 treatments. In contrast, LEAK respiration in trout muscle were higher for mitochondria from fish fed  
376 a low n-3 HUFA diet than for mitochondria from fish fed a high n-3 HUFA diet (Guderley et al., 2008).  
377 Another experiment in trout has shown the opposite effect: animals fed a lower n-3 HUFA diet  
378 displayed lower LEAK respiration in muscle mitochondria (Martin et al., 2013). We stress that it is  
379 entirely possible for the mitochondrial LEAK response to dietary content in n-3 HUFA to vary among  
380 individuals, species and other environmental factors, but also that the consequence on the proton  
381 leakage might depend on the magnitude and duration of the dietary treatment. Equivocal support  
382 may indicate that the responses of LEAK to changes in membrane fatty acid composition does not fall  
383 along a linear response curve, as typically assumed. Instead, the effect of dietary content in n-3 HUFA  
384 on membrane composition, and in turn proton permeability might be biphasic (Abbott et al., 2010)  
385 and might promote non-linear response of LEAK. While testing a large range of n-3 HUFA dietary  
386 content was beyond the scope of the present study, it may only be possible to explain contrasted  
387 pattern of LEAK response if many dietary levels of n-3 HUFA are considered.

388 In our study, mullets from the same food treatment displayed important individual variation  
389 in mitochondrial efficiency that covary with membrane fatty acid composition: individual that had  
390 higher EPA and DHA content in their membranes had mitochondria that synthesized ATP more

391 efficiently than those of individuals with lower EPA and DHA content. Previous studies suggested that  
392 variation in FA composition of the mitochondrial inner membrane can influence the mitochondrial  
393 membrane conductance of protons, and in turn the proportion of oxygen used to offset the proton  
394 leakage (Hulbert et al., 2007), leading to variation in the efficiency of ATP production (Brand, 2005).  
395 However, this does not appear to be the case in the present study, as LEAK did not covary with  
396 ATP/O ratio and membrane fatty acid composition. An explanation for this discrepancy might lie in  
397 the fact that mitochondrial efficiency also depends on protein abundance and activity of the  
398 mitochondrial inner membrane-bound complexes involved in oxidative phosphorylation (i.e. electron  
399 transport complexes and ATP synthase). This alternative explanation is based on the fact that fatty  
400 acid composition of membrane lipids may affect lipid–protein interactions and therefore the function  
401 of embedded proteins (Brenner, 1984). As well as varying with membrane FA composition and  
402 protein function, mitochondrial ATP/O ratio can shift in response to energy substrate use (Brand,  
403 2005). Previous work in Atlantic salmon has demonstrated that individual variation in DHA and EPA in  
404 muscle content was associated with differences in the expression of genes involved in lipid  
405 catabolism and carbohydrate metabolism (Horn et al., 2019). However, further research is needed to  
406 determine whether differences in energy substrates utilization determine individual variation in  
407 mitochondrial efficiency in mullet.

408           Some mullets on the low n-3 HUFA dietary treatment had actually higher EPA and DHA  
409 contents than others on the high n-3 HUFA dietary treatment that were eating almost 15 times as  
410 much EPA and DHA. Individual variation in membrane fatty acid composition is likely to be a  
411 complex, integrative characteristics influenced by several metabolic pathways. If individual  
412 differences in fatty acid membrane composition covary with the rates of lipid assimilation,  
413 biosynthesis and degradation, it is important to recognize that fatty acid composition may vary with  
414 pathways that are generally neglected. For example, ability to biosynthesis EPA and DHA in marine  
415 fish is very limited, as it is generally insufficient to compensate dietary deficiency (Tocher, 2003), but  
416 the link between individual variation in n-3 HUFA content and their rate of biosynthesis might only  
417 appear across individuals eating the same amount of n-3 HUFA. Another explanation might be an  
418 individual heterogeneity in the rate of degradation of EPA and DHA, while also considered minor in  
419 fish (McKenzie, 2001). Individual variation in the rate of assimilation may also be significant for n-3  
420 HUFA content in membrane. Regardless of their food intake, individual fish that have higher levels of  
421 EPA and DHA in membrane lipids may have preferentially retained these fatty acids from their diet.  
422 Our observations illustrate that an understanding of individual variability in membrane fatty acid  
423 composition can be gained only through consideration of differential metabolic pathways of fatty  
424 acids.

425 The individual covariation between mitochondrial efficiency and membrane fatty acid  
426 composition we observed might be because higher EPA and DHA contents in the membrane promote  
427 higher efficiency of the mitochondria, as explained above. However, given that our study is  
428 correlative, it is perhaps high mitochondrial efficiency that may promote membranes with relatively  
429 high levels of EPA and DHA, because more ATP is available to fuel metabolic pathways that retain  
430 dietary n-3 HUFA. Assimilation of fatty acids in the intestine can be energetically costly (Mansbach  
431 and Gorelick, 2007), and for example, fish that have higher efficiency to make ATP may actually have  
432 higher assimilation rate of EPA and DHA compared with fish at lower mitochondrial efficiency. The  
433 variation in mitochondrial efficiency of muscle tissue studied here might be representative of the  
434 mitochondrial efficiency in other tissues, including intestine, although previous studies looking at  
435 correlation of mitochondrial efficiency across tissues in the same individual have shown equivocal  
436 results (Salin et al., 2019). Further study looking at mitochondrial metabolism in different tissues will  
437 be necessary to determine if golden grey mullets are able to improve their mitochondrial efficiency  
438 across multiple tissues.

439 Flexibility in mitochondrial efficiency may be particularly important since the capacity of the  
440 mitochondria to produce ATP can set limits on the capacity of an organism to respond to  
441 environmental changes (Blier et al., 2013; Sokolova et al., 2012). Our data imply that the greater  
442 mitochondrial efficiency induced by the Low n-3 HUFA diet might benefit for the ability of the  
443 mitochondrial to make ATP for energy-demanding cellular processes when reduction in EPA and DHA  
444 availability in food web. Information on the consequences of individual heterogeneity in  
445 mitochondrial efficiency on fish performance would allow a better understanding of the effect of  
446 decline in EPA and DHA availability in marine food web. Further research should focus on identifying  
447 the individual variation in metabolic pathway of EPA and DHA. This type of variation may be very  
448 important in an evolutionary context as well, not only generating phenotypic variation among  
449 individuals, but also allowing animals to reduce the energy costs of making ATP by increasing the  
450 mitochondrial efficiency.

451  
452 ACKNOWLEDGEMENTS: We thank Salomé Ducos for help with fish handling and José-Luis Zambonino  
453 Infante for designing the diets. We thank the three referees for helpful comments that improved the  
454 manuscript.

455  
456 [CRediT author statement](#): KS, MMR, FLG, PS and MV conceived the ideas and designed methodology.  
457 KS, MMR, NG, ED, FLG and MV collected the data. KS, MMR, NG, FLG, PS and MV analysed the data.  
458 KS led the writing of the manuscript except for section 2.3 written by FLG; MMR, FLG, PS and MV  
459 revised the manuscript and added comments. All authors gave final approval for publication.



460

461 DECLARATION OF INTEREST: The authors declare that they have no known competing financial  
462 interests or personal relationships that could have appeared to influence the work reported in this  
463 paper.

464

465 DATA ACCESSIBILITY: The dataset supporting this article will be made available by archiving it in the  
466 Dryad Digital Repository.

467

468 FUNDING: This work is a contribution to the project ECONAT Axe 1 - Ressources Marines Littorales:  
469 qualité et éco-valorisation, funded by the Contrat de Plan Etat-Région and the CNRS and the  
470 European Regional Development Fund.

471

## 472 **References**

- 473 Abbott, S.K., Else, P.L., Hulbert, A.J., 2010. Membrane fatty acid composition of rat skeletal muscle is  
474 most responsive to the balance of dietary n-3 and n-6 PUFA. *British Journal of Nutrition* 103, 522-  
475 529.
- 476 Alimuddin, Yoshizaki, G., Kiron, V., Satoh, S., Takeuchi, T., 2005. Enhancement of EPA and DHA  
477 biosynthesis by over-expression of masu salmon Delta 6-desaturase-like gene in zebrafish. *Transgenic*  
478 *Res.* 14, 159-165.
- 479 Arts, M.T., Kohler, C.C., 2009. Health and condition in fish: the influence of lipids on membrane  
480 competency and immune response, in: Kainz, M., Brett, M.T., Arts, M.T. (Eds.), *Lipids in Aquatic*  
481 *Ecosystems*. Springer New York, New York, NY, pp. 237-256.
- 482 Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan,  
483 A.J., Falkowski, P.G., Letelier, R.M., Boss, E.S., 2006. Climate-driven trends in contemporary ocean  
484 productivity. *Nature* 444, 752-755.
- 485 Bermudez, R., Feng, Y., Roleda, M.Y., Tatters, A.O., Hutchins, D.A., Larsen, T., Boyd, P.W., Hurd, C.L.,  
486 Riebesell, U., Winder, M., 2015. Long-term conditioning to elevated pCO<sub>2</sub> and warming influences the  
487 fatty and amino acid composition of the diatom *Cylindrotheca fusiformis*. *Plos One* 10.
- 488 Blier, P.U., Lemieux, H., Pichaud, N., 2013. Holding our breath in our modern world: will mitochondria  
489 keep the pace with climate changes? *Canadian Journal of Zoology* 92, 591-601.
- 490 Bottje, W.G., Carstens, G.E., 2009. Association of mitochondrial function and feed efficiency in  
491 poultry and livestock species. *Journal of Animal Science* 87, E48-E63.
- 492 Bouchard, P., Guderley, H., 2003. Time course of the response of mitochondria from oxidative muscle  
493 during thermal acclimation of rainbow trout, *Oncorhynchus mykiss*. *J. Exp. Biol.* 206, 3455-3465.
- 494 Brand, M.D., 2000. Uncoupling to survive? The role of mitochondrial inefficiency in ageing.  
495 *Experimental Gerontology* 35, 811-820.
- 496 Brand, M.D., 2005. The efficiency and plasticity of mitochondrial energy transduction. *Biochemical*  
497 *Society Transactions* 33, 897-904.
- 498 Brand, M.D., Couture, P., Hulbert, A.J., 1994. Liposomes from mammalian liver mitochondria are  
499 more polyunsaturated and leakier to protons than those from reptiles. *Comparative Biochemistry*  
500 *and Physiology Part B: Comparative Biochemistry* 108, 181-188.
- 501 Brand, M.D., Nicholls, D.G., 2011. Assessing mitochondrial dysfunction in cells. *Biochemical Journal*  
502 435, 297-312.
- 503 Brenner, R.R., 1984. Effect of unsaturated-acids on membrane-structure and enzyme-kinetics.  
504 *Progress in Lipid Research* 23, 69-96.



505 Brookes, P.S., Buckingham, J.A., Tenreiro, A.M., Hulbert, A.J., Brand, M.D., 1998. The proton  
506 permeability of the inner membrane of liver mitochondria from ectothermic and endothermic  
507 vertebrates and from obese rats: correlations with standard metabolic rate and phospholipid fatty  
508 acid composition. *Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology*  
509 *119*, 325-334.

510 Chinopoulos, C., Kiss, G., Kawamata, H., Starkov, A.A., 2014. Chapter seventeen - Measurement of  
511 ADP-ATP exchange in relation to mitochondrial transmembrane potential and oxygen consumption,  
512 in: Lorenzo, G., Guido, K. (Eds.), *Methods in Enzymology*, Elsevier academic press inc, San Diego, pp.  
513 333-348.

514 Chinopoulos, C., Vajda, S., Csanády, L., Mándi, M., Mathe, K., Adam-Vizi, V., 2009. A novel kinetic  
515 assay of mitochondrial ATP-ADP exchange rate mediated by the ANT. *Biophysical Journal* *96*, 2490-  
516 2504.

517 Coen, P.M., Jubrias, S.A., Distefano, G., Amati, F., Mackey, D.C., Glynn, N.W., Manini, T.M.,  
518 Wohlgenuth, S.E., Leeuwenburgh, C., Cummings, S.R., Newman, A.B., Ferrucci, L., Toledo, F.G.S.,  
519 Shankland, E., Conley, K.E., Goodpaster, B.H., 2012. Skeletal muscle mitochondrial energetics are  
520 associated with maximal aerobic capacity and walking speed in older adults. *The Journals of*  
521 *Gerontology Series A: Biological Sciences and Medical Sciences* *68*, 447-555.

522 da Motta Pacheco, L.F.C., Uribe, E., Pino, J., Troncoso, J., Quiróz, A., 2014. The effect of UV light and  
523 CO<sub>2</sub> in the production of polyunsaturated aldehydes in *Skeletonema costatum* (Bacillariophyceae).  
524 *American Journal of Plant Sciences* *5*, 3632.

525 Distefano, G., Standley, R.A., Zhang, X.L., Carnero, E.A., Yi, F., Cornell, H.H., Coen, P.M., 2018.  
526 Physical activity unveils the relationship between mitochondrial energetics, muscle quality, and  
527 physical function in older adults. *J. Cachexia Sarcopenia Muscle* *9*, 279-294.

528 Fontaine, E.M., Moussa, M., Devin, A., Garcia, J., Ghisolfi, J., Rigoulet, M., Leverve, X.M., 1996. Effect  
529 of polyunsaturated fatty acids deficiency on oxidative phosphorylation in rat liver mitochondria.  
530 *Biochim. Biophys. Acta-Bioenerg.* *1276*, 181-187.

531 Galloway, A.W.E., Winder, M., 2015. Partitioning the Relative Importance of Phylogeny and  
532 Environmental Conditions on Phytoplankton Fatty Acids. *PLOS ONE* *10*, e0130053.

533 Ghanizadeh Kazerouni, E., Franklin, C.E., Seebacher, F., 2016. UV-B exposure reduces locomotor  
534 performance by impairing muscle function but not mitochondrial ATP production. *J. Exp. Biol.* *219*,  
535 96-102.

536 Guderley, H., Kraffe, E., Bureau, W., Bureau, D.P., 2008. Dietary fatty acid composition changes  
537 mitochondrial phospholipids and oxidative capacities in rainbow trout red muscle. *Journal of*  
538 *Comparative Physiology B-Biochemical Systemic and Environmental Physiology* *178*, 385-399.

539 Hamel, S., Gaillard, J.-M., Yoccoz, N.G., 2018. Introduction to: Individual heterogeneity – the causes  
540 and consequences of a fundamental biological process. *Oikos* *127*, 643-647.

541 Herbst, E.A.F., Paglialunga, S., Gerling, C., Whitfield, J., Mukai, K., Chabowski, A., Heigenhauser, G.J.F.,  
542 Spriet, L.L., Holloway, G.P., 2014. Omega-3 supplementation alters mitochondrial membrane  
543 composition and respiration kinetics in human skeletal muscle. *The Journal of Physiology* *592*, 1341-  
544 1352.

545 Hixson, S.M., Arts, M.T., 2016. Climate warming is predicted to reduce omega-3, long-chain,  
546 polyunsaturated fatty acid production in phytoplankton. *Global Change Biology* *22*, 2744-2755.

547 Horn, S.S., Sonesson, A.K., Krasnov, A., Moghadam, H., Hillestad, B., Meuwissen, T.H.E., Ruyter, B.,  
548 2019. Individual differences in EPA and DHA content of Atlantic salmon are associated with gene  
549 expression of key metabolic processes. *Scientific Reports* *9*.

550 Hulbert, A.J., Pamplona, R., Buffenstein, R., Buttemer, W.A., 2007. Life and death: metabolic rate,  
551 membrane composition, and life span of animals. *Physiol Rev* *87*, 1175-1213.

552 Hulbert, A.J., Turner, N., Storlien, L.H., Else, P.L., 2005. Dietary fats and membrane function:  
553 implications for metabolism and disease. *Biological Reviews* *80*, 155-169.

554 Ishizaki, Y., Masuda, R., Uematsu, K., Shimizu, K., Arimoto, M., Takeuchi, T., 2001. The effect of  
555 dietary docosahexaenoic acid on schooling behaviour and brain development in larval yellowtail.  
556 *Journal of Fish Biology* *58*, 1691-1703.

557 Jahn, M., Seebacher, F., 2019. Cost of transport is a repeatable trait but is not determined by  
558 mitochondrial efficiency in zebrafish (*Danio rerio*). The Journal of Experimental Biology 222,  
559 jeb201400.

560 Jeromson, S., Hunter, D.J., 2014. Influencing mitochondrial membrane composition and  
561 bioenergetics through omega-3 supplementation. The Journal of Physiology 592, 1913-1914.

562 Kadenbach, B., 2003. Intrinsic and extrinsic uncoupling of oxidative phosphorylation. Biochim.  
563 Biophys. Acta-Bioenerg. 1604, 77-94.

564 Kang, J.X., 2011. Omega-3: A link between global climate change and human health. Biotechnology  
565 Advances 29, 388-390.

566 Kraffe, E., Marty, Y., Guderley, H., 2007. Changes in mitochondrial oxidative capacities during thermal  
567 acclimation of rainbow trout *Oncorhynchus mykiss*: roles of membrane proteins, phospholipids and  
568 their fatty acid compositions. J. Exp. Biol. 210, 149-165.

569 Lebreton, B., Richard, P., Parlier, E.P., Guillou, G., Blanchard, G.F., 2011. Trophic ecology of mullets  
570 during their spring migration in a European saltmarsh: A stable isotope study. Estuarine Coastal and  
571 Shelf Science 91, 502-510.

572 Mansbach, C.M., II, Gorelick, F., 2007. Development and Physiological Regulation of Intestinal Lipid  
573 Absorption. II. Dietary lipid absorption, complex lipid synthesis, and the intracellular packaging and  
574 secretion of chylomicrons. American Journal of Physiology-Gastrointestinal and Liver Physiology 293,  
575 G645-G650.

576 Martin, N., Bureau, D.P., Marty, Y., Kraffe, E., Guderley, H., 2013. Dietary lipid quality and  
577 mitochondrial membrane composition in trout: responses of membrane enzymes and oxidative  
578 capacities. Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology  
579 183, 393-408.

580 Mathieu-Resuge, M., Kraffe, E., Le Grand, F., Boens, A., Bideau, A., Lluch-Cota, S.E., Racotta, I.S.,  
581 Schaal, G., 2019. Trophic ecology of suspension-feeding bivalves inhabiting a north-eastern Pacific  
582 coastal lagoon: Comparison of different biomarkers. Marine Environmental Research 145, 155-163.

583 Mazon, C., Bruce, M., Bell, J.G., Davie, A., Alorend, E., Jordan, N., Rees, J., Papanikos, N., Porter, M.,  
584 Bromage, N., 2003. Dietary lipid enhancement of broodstock reproductive performance and egg and  
585 larval quality in Atlantic halibut (*Hippoglossus hippoglossus*). Aquaculture 227, 21-33.

586 McIntyre, P.B., Reidy Liermann, C.A., Revenga, C., 2016. Linking freshwater fishery management to  
587 global food security and biodiversity conservation. Proceedings of the National Academy of Sciences  
588 113, 12880-12885.

589 McKenzie, D.J., 2001. Effects of dietary fatty acids on the respiratory and cardiovascular physiology of  
590 fish. Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology 128, 607-621.

591 McKenzie, D.J., Higgs, D.A., Dosanjh, B.S., Deacon, G., Randall, D.J., 1998. Dietary fatty acid  
592 composition influences swimming performance in Atlantic salmon (*Salmo salar*) in seawater. Fish  
593 Physiol. Biochem. 19, 111-122.

594 Morash, A.J., Bureau, D.P., McClelland, G.B., 2009. Effects of dietary fatty acid composition on the  
595 regulation of carnitine palmitoyltransferase (CPT) I in rainbow trout (*Oncorhynchus mykiss*).  
596 Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology 152, 85-93.

597 Mourente, G., Tocher, D.R., 1993. Incorporation and metabolism of C-14-labeled polyunsaturated  
598 fatty-acids in wild-caught juveniles of golden gray mullet, *liza-aurata*, *in vivo*. Fish Physiol. Biochem.  
599 12, 119-130.

600 Nogueira, V., Piquet, M.A., Devin, A., Fiore, C., Fontaine, E., Brandolin, G., Rigoulet, M., Leverve, X.M.,  
601 2001. Mitochondrial adaptation to *in vivo* polyunsaturated fatty acid deficiency: Increase in  
602 phosphorylation efficiency. Journal of Bioenergetics and Biomembranes 33, 53-61.

603 Norambuena, F., Morais, S., Emery, J.A., Turchini, G.M., 2015. Arachidonic acid and eicosapentaenoic  
604 acid metabolism in juvenile *Atlantic salmon* as affected by water temperature. Plos One 10, 25.

605 Oboh, A., Kabeya, N., Carmona-Antoñanzas, G., Castro, L.F.C., Dick, J.R., Tocher, D.R., Monroig, O.,  
606 2017. Two alternative pathways for docosahexaenoic acid (DHA, 22:6n-3) biosynthesis are  
607 widespread among teleost fish. Scientific Reports 7, 3889.

608 Pörtner, H.O., Knust, R., 2007. Climate change affects marine fishes through the oxygen limitation of  
609 thermal tolerance. Science 315, 95-97.

610 Ramsey, J.J., Harper, M.E., Humble, S.J., Koomson, E.K., Ram, J.J., Bevilacqua, L., Hagopian, K., 2005.  
611 Influence of mitochondrial membrane fatty acid composition on proton leak and H<sub>2</sub>O<sub>2</sub> production in  
612 liver. *Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology* 140, 99-108.  
613 Robert, K.A., Bronikowski, A.M., 2010. Evolution of senescence in nature: Physiological evolution in  
614 populations of garter snake with divergent life histories. *American Naturalist* 175, E47-159.  
615 Robin, J.H., Skalli, A., 2007. Incorporation of dietary fatty acid in European sea bass (*Dicentrarchus*  
616 *labrax*) - A methodological approach evidencing losses of highly unsaturated fatty acids. *Aquaculture*  
617 263, 227-237.  
618 Salin, K., Auer, S.K., Anderson, G.J., Selman, C., Metcalfe, N.B., 2016a. Inadequate food intake at high  
619 temperatures is related to depressed mitochondrial respiratory capacity. *J. Exp. Biol.* 219, 1356-1362.  
620 Salin, K., Auer, S.K., Rey, B., Selman, C., Metcalfe, N.B., 2015. Variation in the link between oxygen  
621 consumption and ATP production, and its relevance for animal performance. *Proc. R. Soc. B-Biol. Sci.*  
622 282, 20151028.  
623 Salin, K., Auer, S.K., Rudolf, A.M., Anderson, G.J., Selman, C., Metcalfe, N.B., 2016b. Variation in  
624 metabolic rate among individuals is related to tissue-specific differences in mitochondrial leak  
625 respiration. *Physiological and Biochemical Zoology* 89, 511-523.  
626 Salin, K., Luquet, E., Rey, B., Roussel, D., Voituron, Y., 2012. Alteration of mitochondrial efficiency  
627 affects oxidative balance, development and growth in frog (*Rana temporaria*) tadpoles. *J. Exp. Biol.*  
628 215, 863-869.  
629 Salin, K., Villasevil, E.M., Anderson, G.J., Auer, S.K., Selman, C., Hartley, R.C., Mullen, W., Chinopoulos,  
630 C., Metcalfe, N.B., 2018. Decreased mitochondrial metabolic requirements in fasting animals carry an  
631 oxidative cost. *Functional Ecology* 32, 2149-2157.  
632 Salin, K., Villasevil, E.M., Auer, S.K., Anderson, G.J., Selman, C., Metcalfe, N.B., Chinopoulos, C., 2016c.  
633 Simultaneous measurement of mitochondrial respiration and ATP production in tissue homogenates  
634 and calculation of effective P/O ratios. *Physiological Reports* 4, e13007.  
635 Salin, K., Villasevil Eugenia, M., Anderson Graeme, J., Lamarre Simon, G., Melanson Chloé, A.,  
636 McCarthy, I., Selman, C., Metcalfe Neil, B., 2019. Differences in mitochondrial efficiency explain  
637 individual variation in growth performance. *Proceedings of the Royal Society B: Biological Sciences*  
638 286, 20191466.  
639 Sokolova, I.M., Frederich, M., Bagwe, R., Lannig, G., Sukhotin, A.A., 2012. Energy homeostasis as an  
640 integrative tool for assessing limits of environmental stress tolerance in aquatic invertebrates.  
641 *Marine Environmental Research* 79, 1-15.  
642 Szmecinski, H., Lakowicz, J.R., 1996. Fluorescence lifetime characterization of magnesium probes:  
643 Improvement of Mg<sup>2+</sup> dynamic range and sensitivity using phase-modulation fluorometry. *Journal of*  
644 *Fluorescence* 6, 83-95.  
645 Team, R.C., 2017. R: A language and Environment for Statistical, 3.6.1. ed. R Foundation for Statistical  
646 Computing, Vienna, Austria.  
647 Tocher, D.R., 2003. Metabolism and functions of lipids and fatty acids in teleost fish. *Reviews in*  
648 *Fisheries Science* 11, 107-184.  
649 Vagner, M., Lacoue-Labarthe, T., Zambonino-Infante, J.-L., Mazurais, D., Dubillot, E., Le Delliou, H.,  
650 Quazuguel, P., Lefrançois, C., 2015. Depletion of essential fatty acids in the food source affects  
651 aerobic capacities of the golden grey mullet *Liza aurata* in a warming seawater context. *Plos One* 10,  
652 19.  
653 Vagner, M., Zambonino-Infante, J.-L., Mazurais, D., Imbert-Auvray, N., Ouillon, N., Dubillot, E., Le  
654 Delliou, H., Akbar, D., Lefrançois, C., 2014. Reduced n-3 highly unsaturated fatty acids dietary content  
655 expected with global change reduces the metabolic capacity of the golden grey mullet. *Marine*  
656 *Biology* 161, 2547-2562.  
657 Yu, L., Fink, B., Herlein, J., Oltman, C., Lamping, K., Sivitz, W., 2014. Dietary fat, fatty acid saturation  
658 and mitochondrial bioenergetics. *Journal of Bioenergetics and Biomembranes* 46, 33-44.  
659

660 **Table 1:** Mean  $\pm$  SEM eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) content and sum of  
 661 EPA and DHA content ( $\Sigma$  EPA + DHA) in muscle membrane fatty acids (percentage of the EPA and DHA  
 662 mass per total fatty acids mass in membrane, %), of juvenile golden grey mullet given High (n=11) or  
 663 Low (n=12) omega-3 highly unsaturated fatty acids (n-3 HUFA) diet. Different letters within a row  
 664 indicate significant differences between diet treatments (Wilcoxon tests, at the significant level  $p <$   
 665 0.05). More details on FA composition of muscle membranes are provided Table S3.

666

<i>Muscle membrane FA composition (%)</i>	<b>High n-3 HUFA fish</b>	<b>Low n-3 HUFA fish</b>
<i>EPA</i>	9.8 $\pm$ 0.3 <sup>a</sup>	5.7 $\pm$ 1.0 <sup>b</sup>
<i>DHA</i>	20.8 $\pm$ 0.7 <sup>a</sup>	10.1 $\pm$ 2.0 <sup>b</sup>
$\Sigma$ EPA + DHA	30.6 $\pm$ 0.8 <sup>a</sup>	15.8 $\pm$ 3.0 <sup>b</sup>

667

668

669 **Table 2:** Results from linear model analyses of muscle mitochondrial efficiency (ATP/O ratio) and  
 670 respiratory capacities to offset the proton leak (LEAK respiration) in juvenile golden grey mullet as a  
 671 function of the sum of eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA) content -  $\Sigma$  EPA +  
 672 DHA in muscle (percentage of the EPA and DHA mass per total fatty acid mass in membrane). Bold  
 673 denotes significant results.

674

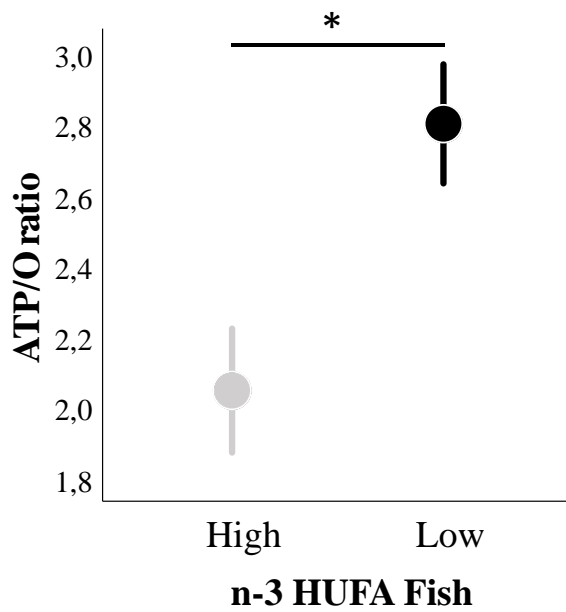
<i>Dependant variable</i>	<i>Source of variation</i>	<i>Parameter estimate <math>\pm</math> SEM</i>	<i>t-value</i>	<i>p-value</i>
<b>ATP/O ratio</b>	Intercept	2.21 $\pm$ 0.23	7.978	<b>&lt; 0.001</b>
	<b><math>\Sigma</math> EPA + DHA</b>	<b>0.04 <math>\pm</math> 0.01</b>	<b>2.513</b>	<b>0.021</b>
	<b>diet</b>	<b>1.30 <math>\pm</math> 0.31</b>	<b>4.232</b>	<b>&lt; 0.001</b>
<b>LEAK respiration</b>	Intercept	56.59 $\pm$ 6.45	8.769	<0.001
	$\Sigma$ EPA + DHA	0.04 $\pm$ 0.34	-0.104	0.919
	diet	2.61 $\pm$ 7.17	0.364	0.720

675

676 FIGURES

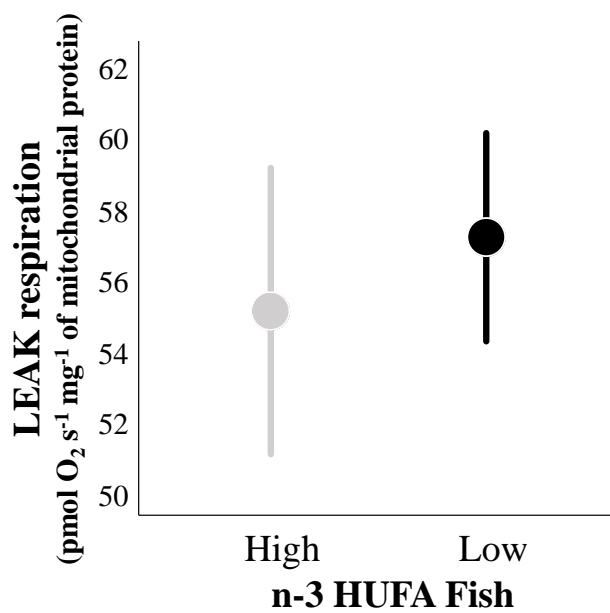
677 **Figure 1.** Effect of omega-3 highly unsaturated fatty acids (n-3 HUFA) dietary content on (a)  
678 mitochondrial efficiency estimated as ATP/O ratio ( $t_{21} = -3.107$ ,  $p = 0.005$ ) and (b) mitochondrial LEAK  
679 respiration ( $t_{21} = -0.423$ ,  $p = 0.677$ ) of muscle of golden grey mullet that were kept either on High  
680 (n=11) or Low (n=12) n-3 HUFA diet. Data are plotted as mean  $\pm$  SEM. \* denotes significant effect.

681 (a)



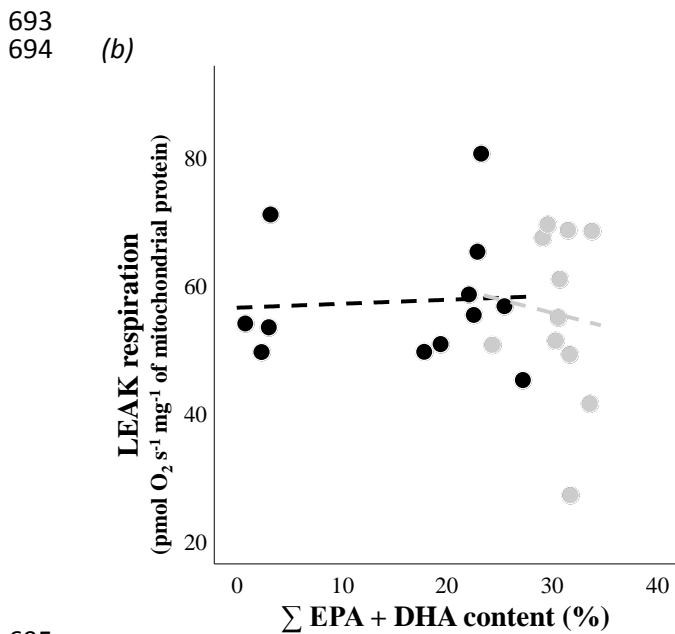
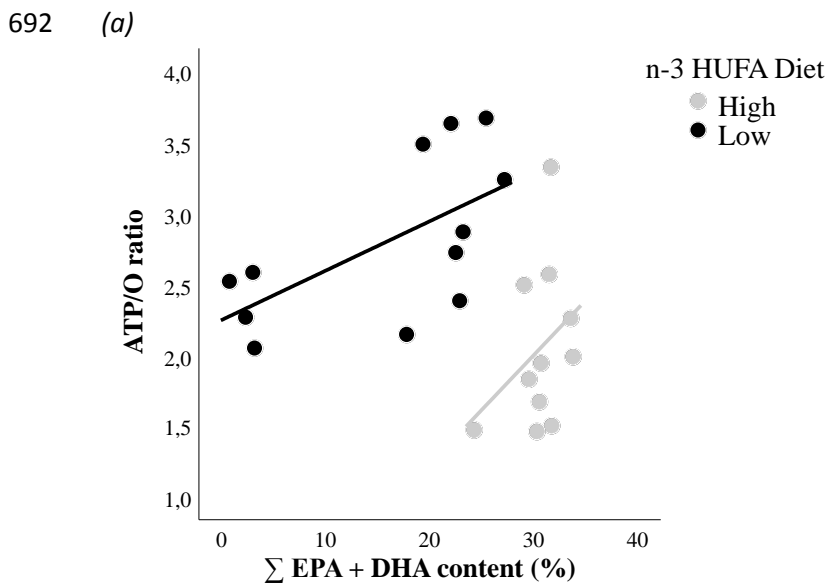
682

683 (b)



684

685 **Figure 2.** Relationships between the mitochondrial function and membrane lipid content in  
 686 eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) content (expressed as  $\Sigma$  EPA + DHA  
 687 content, percentage of the sum of EPA and DHA mass per total fatty acid mass in membranes) of  
 688 muscle of juvenile golden grey mullet fed on a Low (n=12) versus High (n=11) omega-3 highly  
 689 unsaturated fatty acid (n-3 HUFA) diet. Mitochondrial efficiency (ATP/O ratio) in relation to (a)  $\Sigma$  EPA  
 690 + DHA content, (b) LEAK respiration in relation to  $\Sigma$  EPA + DHA content. Continuous lines show  
 691 significant effects, dashed lines show non-significant effects (see Table 2 for details).



695  
696

697 **ELECTRONIC SUPPLEMENTARY MATERIAL**

698 **Table S1:** (a) Ingredient (in g 100 g<sup>-1</sup>) and (b) fatty acid (FA) composition expressed as a percentage  
 699 of FA mass per total FA mass (% mean ± standard error of the mean; n = 3) in the High and Low  
 700 omega-3 highly unsaturated fatty acid (n-3 HUFA) diets (made at INRA, Donzag, France). Only FA that  
 701 occur above 1 % in at least a treatment group are represented. Bold denotes significant results of  
 702 one-way ANOVA. Assumptions of normal distribution and homoscedasticity of residuals were met.

703 (a)

Ingredients <sup>a</sup>	High n-3 HUFA diet	Low n-3 HUFA diet
Fish meal LT 94	17	17
Casein	30	30
Rapeseed oil	2	10
Fish oil	8	0
Precooked starch	30	30
Vitamin mixture <sup>b</sup>	8	8
Mineral mixture <sup>c</sup>	4	4
Betaine	1	1

704

705 <sup>a</sup> Sources: fish meal LT 94: Norse (Fyllingsdalen, Norway); casein: Sigma-Aldrich (Germany); rapeseed oil:  
 706 Système U (Créteil, France); fish oil: pure cod oil Cooper (Melun, France); precooked starch: Prégéflo Roquette  
 707 Frères (Lestrem, France); vitamin mixture (INRA Jouy-en-Josas, France)

708 <sup>b</sup> Vitamin mixture (g kg<sup>-1</sup> vitamin mix): retinyl acetate 1; cholecalciferol 2.5; D $\alpha$ -tocopheryl acetate 5;  
 709 menadione 1; thiamine-HCl 0.1; riboflavin 0.4; D-calcium pantothenate 2; pyridoxine-HCl 0.3; cyanocobalamin  
 710 1; niacin 1; choline 200; ascorbic acid (ascorbyl polyphosphate) 5; folic acid 0.1; D-biotin 1; mesoinositol 30.

711 <sup>c</sup> Mineral mixture (g kg<sup>-1</sup> mineral mix): KCl 90; KI 0,04; CaHPO<sub>4</sub>·2H<sub>2</sub>O 500; NaCl 40; CuSO<sub>4</sub>·5H<sub>2</sub>O 3; ZnSO<sub>4</sub>·7H<sub>2</sub>O 4;  
 712 CoSO<sub>4</sub> 0.02; FeSO<sub>4</sub>·7H<sub>2</sub>O 20; MnSO<sub>4</sub>·H<sub>2</sub>O 3; CaCO<sub>3</sub> 215; MgOH 124; Na<sub>2</sub>SeO<sub>3</sub> 0 03; NaF 1.

713

714 (b)

Diet FA composition (%)	High n-3 HUFA	Low n-3 HUFA	F	Df	p-value
<b>14 :0</b>	<b>4.30 ± 0.20</b>	<b>0.41 ± 0.02</b>	<b>362.2</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>16 :0</b>	<b>18.67 ± 0.80</b>	<b>6.10 ± 0.26</b>	<b>223.6</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>18 :0</b>	<b>4.59 ± 0.21</b>	<b>1.91 ± 0.09</b>	<b>142.7</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>16 :1n-7</b>	<b>4.83 ± 0.11</b>	<b>0.44 ± 0.01</b>	<b>1630</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>18 :1n-9</b>	<b>25.04 ± 0.23</b>	<b>56.74 ± 0.30</b>	<b>7004</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>18 :1n-7</b>	<b>2.56 ± 0.36</b>	<b>0.05 ± 0.05</b>	<b>46.2</b>	<b>1</b>	<b>&lt; 0.01</b>
20 :1n-9	1.82 ± 0.08	4.94 ± 2.09	2.2	1	0.21
<b>18 :2n-6</b>	<b>5.06 ± 0.36</b>	<b>15.13 ± 1.82</b>	<b>29.6</b>	<b>1</b>	<b>&lt; 0.01</b>
<b>18 :3n-3</b>	<b>2.42 ± 0.25</b>	<b>6.49 ± 1.03</b>	<b>14.7</b>	<b>1</b>	<b>0.02</b>
<b>20 :4n-6</b>	<b>1.38 ± 0.07</b>	<b>0.27 ± 0.04</b>	<b>205.1</b>	<b>1</b>	<b>&lt; 0.001</b>
<b>20 :5n-3</b>	<b>6.63 ± 0.60</b>	<b>0.39 ± 0.07</b>	<b>106.3</b>	<b>1</b>	<b>&lt; 0.001</b>
22 :5n-3	1.64 ± 0.09	0.88 ± 0.31	5.5	1	0.07
<b>22 :6n-3</b>	<b>10.95 ± 0.63</b>	<b>0.78 ± 0.14</b>	<b>246.3</b>	<b>1</b>	<b>&lt; 0.001</b>

715

716 **Table S2:** Mean  $\pm$  SEM mitochondrial function of muscle of golden grey mullet fed with High (n=11)  
 717 and Low omega-3 highly unsaturated fatty acid (n-3 HUFA) diet. Rate of ATP production, rate of  
 718 oxygen consumption to support ATP production (OXPHOS respiration), and to offset the proton  
 719 leakage (LEAK respiration). Fluxes are expressed in pmol ATP produced and oxygen consumed  $s^{-1} mg^{-1}$   
 720 of mitochondrial protein. The respiratory control ratio (RCR), an index of mitochondrial coupling  
 721 (Brand and Nicholls, 2011) was calculated as the ratio of OXPHOS respiration to the LEAK respiration.

*Muscle mitochondrial function*    **High n-3 HUFA fish**    **Low n-3 HUFA fish**

<i>ATP production</i>	3267.6 $\pm$ 445.8	3869.7 $\pm$ 237.4
<i>OXPHOS respiration</i>	836.8 $\pm$ 112.0	733.6 $\pm$ 60.8
<i>LEAK respiration</i>	55.1 $\pm$ 4.0	57.1 $\pm$ 2.9
<i>RCR</i>	14.6 $\pm$ 1.5	13.0 $\pm$ 1.0

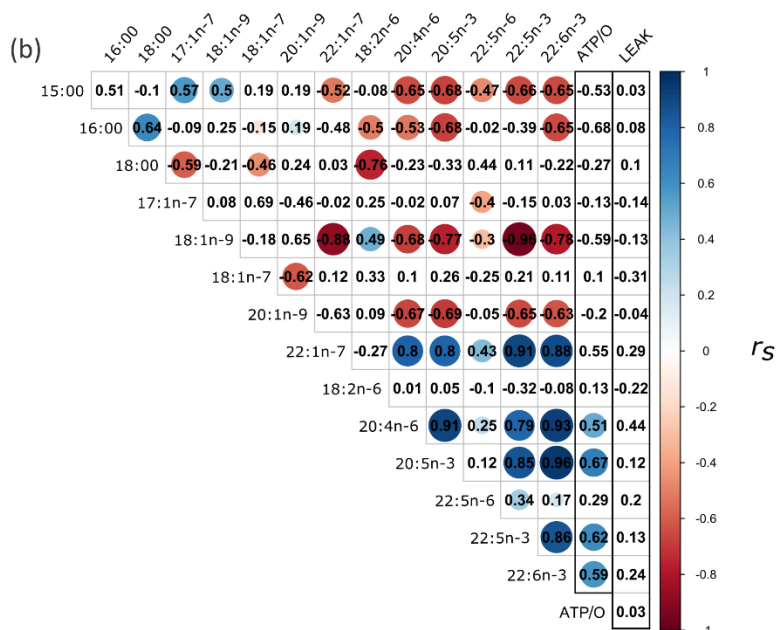
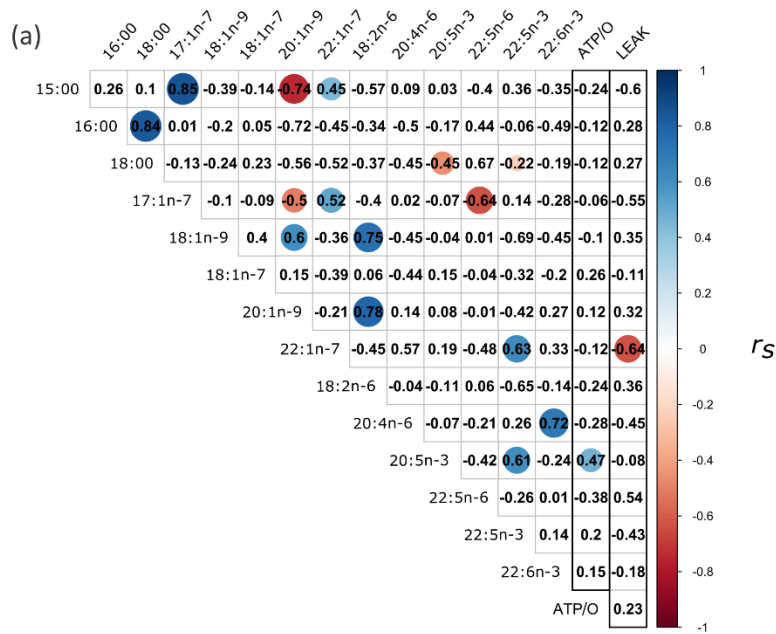
722  
 723 **Table S3:** Results from Kruskal-Wallis tests comparing fatty acid contents (percent of FA mass per  
 724 total FA mass) in membrane lipids of the muscle of golden grey mullet (*Chelon auratus*) that were  
 725 either fed a High or Low omega-3 highly unsaturated fatty acid (n-3 HUFA) diet. Only FA that occur  
 726 above 1 % in at least a treatment group are represented. Means are expressed  $\pm$  standard error of  
 727 the mean. Bold denotes significant results. N = 11-12 per treatment group.

<i>Muscle membrane FA composition (%)</i>	<i>High n-3 HUFA</i>	<i>Low n-3 HUFA</i>	<i>Chi<sup>2</sup></i>	<i>p-value</i>
<b>15 :0</b>	<b>0.97 <math>\pm</math> 0.08</b>	<b>1.68 <math>\pm</math> 0.29</b>	<b>4.125</b>	<b>0.04</b>
16 :0	18.49 $\pm$ 0.75	21.15 $\pm$ 2.20	0.015	0.902
18 :0	9.78 $\pm$ 0.39	9.91 $\pm$ 1.44	0.379	0.54
17 :1n-7	1.29 $\pm$ 0.09	1.66 $\pm$ 0.17	1.83	0.18
<b>18 :1n-9</b>	<b>11.42 <math>\pm</math> 0.46</b>	<b>19.32 <math>\pm</math> 1.98</b>	<b>15.51</b>	<b>&lt; 0.001</b>
18 :1n-7	2.95 $\pm$ 0.07	2.81 $\pm$ 0.08	1.67	0.20
<b>20 :1n-9</b>	<b>1.03 <math>\pm</math> 0.06</b>	<b>1.41 <math>\pm</math> 0.09</b>	<b>8.72</b>	<b>0.003</b>
22 :1n-7	1.42 $\pm$ 0.10	1.40 $\pm$ 0.19	0.034	0.85
<b>18 :2n-6</b>	<b>1.70 <math>\pm</math> 0.24</b>	<b>4.95 <math>\pm</math> 0.72</b>	<b>11.05</b>	<b>&lt; 0.001</b>
<b>20 :4n-6</b>	<b>4.16 <math>\pm</math> 0.08</b>	<b>2.31 <math>\pm</math> 0.42</b>	<b>16.5</b>	<b>&lt; 0.001</b>
<b>20 :5n-3</b>	<b>9.82 <math>\pm</math> 0.32</b>	<b>5.70 <math>\pm</math> 1.03</b>	<b>10.64</b>	<b>&lt; 0.001</b>
<b>22 :5n-6</b>	<b>1.35 <math>\pm</math> 0.08</b>	<b>0.89 <math>\pm</math> 0.14</b>	<b>8.37</b>	<b>&lt; 0.01</b>
22 :5n-3	5.58 $\pm$ 0.15	3.97 $\pm$ 0.62	2.76	0.09
<b>22 :6n-3</b>	<b>20.78 <math>\pm</math> 0.66</b>	<b>10.08 <math>\pm</math> 1.96</b>	<b>16.5</b>	<b>&lt; 0.001</b>

729  
 730



731 **Figure S1:** Spearman's correlation analyses between the membrane lipid fatty acids and the  
 732 mitochondrial function of muscle of golden grey mullet fed with (a) High (n=11) and (b) Low omega-3  
 733 highly unsaturated fatty acid (n-3 HUFA) diet. FA composition were calculated as percent of FA mass  
 734 per total FA mass. Only FA that occur above 1 % in at least a treatment group are represented.  
 735 Mitochondrial function were expressed as the mitochondrial efficiency (ATP/O) and the LEAK  
 736 respiration. N = 11-12 per treatment group. The coloured circles represent significant correlations  
 737 between two variables ( $p < 0.05$ ). The numbers inside cells are the associated Spearman's correlation  
 738 ( $r_s$ ).



739