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# Unique thermal sensitivity imposes a cold-water energetic barrier for vertical migrators

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# Supplementary Materials

**This PDF file includes:**


Supplementary Text
Supplementary Figure 1
Tables S1 and S2
Supplementary References

## Supplementary Information

Metabolic Traits and their interrelationships.

$\alpha$ **–Physiological oxygen supply capacity (μmol $O_2$ $g^{-1}h^{-1}kPa^{-1}$)**: The maximum amount of oxygen that can be supplied per unit time, mass and oxygen pressure. The ratio of oxygen demand to supply (i.e. $MR/PO_2$) increases as oxygen declines and/or metabolic rate increases until it reaches a critical $PO_2$ ($P_c$), at which physiological oxygen supply (e.g. ventilation and cardiac output) is operating at its maximum capacity ($\alpha$). The $\alpha$ is a species- and temperature- specific constant that quantifies the oxygen dependency of metabolism.

$$\alpha = MR/P_c$$

**MR – Metabolic Rate (μmol $O_2$ $g^{-1}h^{-1}$):** The rate of aerobic energy usage, estimated from oxygen consumption. The maximum metabolic rate (**MMR**) is the highest achievable MR, typically measured during exercise protocols. At $PO_2$ less than $P_{cmax}$, MMR is directly oxygen dependent. The standard metabolic rate (**SMR**) refers to the fasted, resting metabolic rate at a specified temperature.

**FAS – Factorial Aerobic Scope (no units):** The factorial difference between MMR and SMR, which is equivalent to the factorial difference between $P_{cmax}$ and $P_{cSMR}$. Like MMR, FAS is directly dependent on $PO_2$ below $P_{cmax}$. FAS is a measure of the aerobic capacity to support activities (e.g., growth, reproduction, locomotion) beyond basic maintenance.

$$FAS = MMR/SMR = P_{cmax}/P_c$$

**$P_c$ – The Critical $PO_2$ (kPa):** The $PO_2$ at which oxygen supply reaches its maximum capacity ($\alpha$) for any given metabolic rate (see *Eq. 1*). Equivalently, $P_c$ is the $PO_2$ below which its corresponding metabolic rate becomes oxygen limited. $P_c$ and $P_{cmax}$ refer specifically to the critical $PO_2$s for SMR and MMR, respectively.

***E* – Temperature sensitivity (eV):** The temperature (T) dependence of a given physiological metric is parameterized as $\exp(-E/k_BT)$, where $E$ is the temperature dependence and $k_B$ is the Boltzmann constant. The temperature dependence ($E$) of each metric is the slope of the linear regression of $1/k_BT$ versus the natural log of the metric (i.e. the slope of an Arrhenius plot). The equation below shows the relationships between the temperature sensitivities of each metric.

$$E_{FAS} = E_{MMR} - E_{SMR} = E_{Pcmax} - E_{Pc}$$

**Fig. S1. Metabolic traits and their interrelationships.** A) Maximum metabolic rate (MMR), Standard metabolic rate (SMR), and their critical oxygen pressures ($P_{cmax}$ and $P_{cSMR}$, respectively) are quantitatively related via the oxygen supply capacity, $\alpha$. The factorial aerobic scope (FAS) is the factorial difference between MMR and SMR, or between $P_{cmax}$ and $P_c$, which are quantitatively equivalent. B) Seibel and Deutsch (2020) reported that there is a linear relationship between MMR and $PO_2$ (constancy of oxygen supply capacity across metabolic states from SMR to MMR at a given temperature). This is evident by the nearly perfect correlation between the oxygen supply capacity derived at SMR and $P_c$ and that derived at MMR and measurement $PO_2$ (usually 21 kPa). For hypoxic species (red dots), which have a $P_{cmax}$ well below the measurement $PO_2$, we divided MMR by the prevailing environmental $PO_2$. The slope of the relationship in this figure is 1.0 and the intercept is zero, which means that oxygen supply is the same at the limiting oxygen pressures for any metabolic level between SMR and MMR.

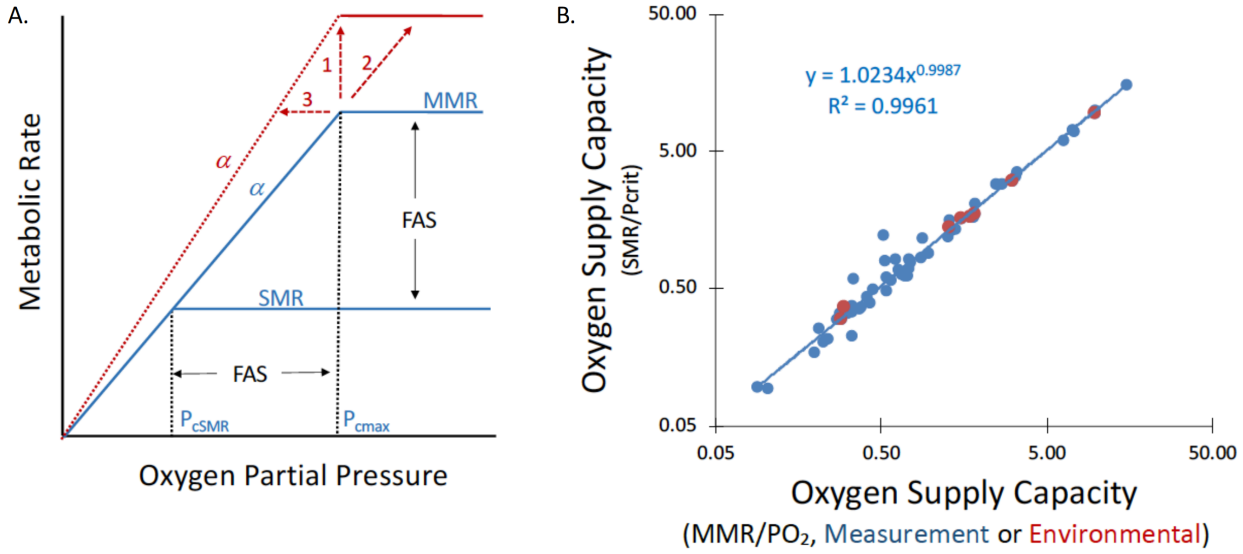

**Table S1.**

*Dosidicus gigas* metabolic traits and their temperature sensitivities (*E;* Values are means ± SEM).

| Temperature (°C) | SMR (μmol $O_2$ $g^{-1}h^{-1}$) | MMR (μmol $O_2$ $g^{-1}h^{-1}$) | $P_{cSMR}$ (kPa) | $\alpha$ (μmol $O_2$ $g^{-1}h^{-1}kPa^{-1}$) |
|---|---|---|---|---|
| 10 | 8.05 ± 0.51 | 17.3 ± 4.32 | 1.86 ± 0.43 | 4.97 |
| 20 | 10.26 ± 0.75 | 23.3 ± 1.96 | 3.50 ± 0.23 | 3.15 |
| 25 | 16.98 ± 0.88 | 69.8 ± 5.25 | 4.65 ± 0.54 | 3.66 |

| Temperature (°C) | $E_{SMR}$ (eV) | $E_{MMR}$ (eV) | $E_{PcSMR}$ (eV) | $E_{\alpha}$ (eV) |
|---|---|---|---|---|
| 10-20 | 0.17 | 0.21 | 0.49 | -0.33 |
| 20-25 | 0.75 | 1.65 | 0.53 | 0.23 |
| 10-25 | 0.33 | 0.60 | 0.51 | -0.18 |

**Table S2**

**Metabolic traits, including the standard metabolic rate (SMR), the critical $PO_2$ for SMR ($P_{cSMR}$), and the oxygen supply capacity ($\alpha$), and their temperature sensitivities for diel vertical migrators.**

| Species (reference) | T (°C) | Mass, g (range) | Mean $MO_2$, μmol $O_2$ $g^{-1}h^{-1}$ (range, n) | Mean $P_{crit}$, kPa (range, n) | $\alpha$, μmol $O_2$ $g^{-1}h^{-1}kPa^{-1}$ | Temperature Sensitivity ($E$, eV) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | SMR | $P_c$ | $\alpha$ |
| **Vertical Migrators** | | | | | | | | |
| *Nyctiphanes simplex** (Euphausiacea) | 10 | 0.037 ± 0.027 (0.007-0.0924) | 7.24 ± 1.44 (4.14 – 9.02, 7) | 2.12± 0.83 (1.16-3.68, 9) | 3.87±1.33 (2.09-5.80; 7) | | | |
| | 20 | 0.067 ± 0.043 (0.008-0.128) | 10.25 ± 1.85 (9.1-11.98, 4) | 4.04 (2.06-6.24; 3) | 2.90 (1.6-4.37; 3) | 0.25 | 0.46 | -0.20 |
| *Tessarabrachion oculatum** (Euphausiacea) | 10 | 0.055 ± 0.014 (0.033-0.076) | 7.30 ± 0.90 (6.1 – 8.44, 10) | 2.02 ± 0.61 (1.29 – 3.18, 10) | 3.88±1.15 (2.49-6.33, 10) | | | |
| | 20 | 0.062 ± 0.46 (0.022-0.086) | 11.93 ± 2.00 (9.42 – 14.26, 6) | 4.04 ± 1.06 (2.20 – 5.01, 6) | 3.28 ±1.62 (2.00-6.00, 6) | 0.35 | 0.49 | -0.12 |
| *Nematobrachion flexipes** (Euphausiacea) | 10 | 0.089 ± 0.004 (0.07-0.10) | 5.17 ± 0.69 (4.26-6.19; 7) | 1.25 ± 0.82 (0.85 – 3.12, 7) | 4.84±1.38 (1.98-6.16, 7) | | | |
| | 20 | 0.045 ± 0.005 (0.045 – 0.112) | 12.33 ± 2.25 (10.12-15.33, 6) | 3.66 ± 0.93 (2.48-5.10, 6) | 3.59±1.18 (1.96-4.83, 6) | 0.62 | 0.76 | -0.21 |
| *Euphausia mucronata** (Euphausiacea) | 10 | 0.26 ± 0.096 (0.038 – 0.35) | 4.84 ± 1.81 (2.21 – 7.87, 20) | 1.39 ± 1.44 (0.61 – 2.18, 20) | 4.07±2.64 (2.98-5.64) | | | |
| | 20 | 0.39 ± 0.10 | 9.22 ± 1.02 (7.2-10.39, 3) | 3.30 ± 1.10 (2.48-3.50, 3) | 2.93±1.09 (1.4-3.57, 3) | 0.46 | .62 | -0.23 |
| *Dosidicus gigas* (Cephalopoda) (*56, 57*) | 10 | | 8.05 ± 0.51 | 1.86 ± 0.43 | 4.97 | | | |
| | 20 | | 10.26 ± 0.75 | 3.50 ± 0.23 | 3.15 | | | |
| | 25 | | 16.69 ± 0.88 | 4.65 ± 0.54 | 3.66 | 0.33 | 0.51 | -0.20 |
| *Euphausia gibboides (58)* | 13 | | 28.0 (dry mass) | 2.25 | Dry mass | | | |
| | 23 | | 43.1 (dry mass) | 4.13 | Dry mass | 0.32 | 0.44 | -0.13 |
| *Euphausia hanseni (59)* | 10 | | 5.19 | 0.97 | 5.35 | | | |
| | 20 | | 14.09 | 3.31 | 4.26 | 0.71 | 0.88 | -0.17 |

| Table S2: Coatal Marine Animals continued | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Gadus morhua (60)* | 18 | | 3.84 | 6.42 | 0.60 | 0.71 | 0.34 | 0.37 |
| | 5 | | 0.9 | 3.49 | 0.26 | | | |
| | 10 | | 1.66 | 4.91 | 0.34 | | | |
| | 15 | | 2.1 | 6.52 | 0.322 | | | |
| | 2 | | 0.75 | 3.2 | 0.23 | | | |
| *Sciaenops ocellatus (61)* | 24 | | 5.78 | 4.2 | 1.38 | 0.43 | 0.24 | 0.19 |
| | 30 | | 8.09 | 5.05 | 1.60 | | | |
| *Cyclopterus lumpus (61)* | 10 | | 2.5 | 7.13 | 0.35 | 0.42 | 0.26 | 0.16 |
| | 16 | | 3.57 | 8.83 | 0.40 | | | |
| *Chromis atripectorais (62)* | 35 | | 7.56 | 4.88 | 1.55 | 1.10 | 0.75 | 0.35 |
| | 33 | | 5.72 | 4.8 | 1.19 | | | |
| | 31 | | 5.15 | 4.31 | 1.19 | | | |
| | 29 | | 3.21 | 3.29 | 0.98 | | | |
| *Salmo salar (63)* | 18 | | 6.37 | 7.56 | 0.84 | 0.33 | 0.19 | 0.14 |
| | 22 | | 9.17 | 9.45 | 0.97 | | | |
| *Morone saxatilis (64)* | 20 | | 2.27 | 5.5 | 0.41 | 0.80 | 0.38 | 0.42 |
| | 26 | | 4.28 | 7.43 | 0.58 | | | |
| *Carcharhinus plumbeus (65)* | 24 | | 4.38 | 8.13 | 0.54 | 0.37 | 0.31 | 0.06 |
| | 28 | | 5.10 | 9.69 | 0.53 | | | |
| | 32 | | 6.41 | 11.25 | 0.57 | | | |
| *Centropristis striata (66)* | 12 | | 1.31 | 3.36 | 0.39 | 0.62 | 0.23 | 0.39 |
| | 17 | | 1.89 | 3.99 | 0.47 | | | |
| | 22 | | 2.72 | 4.73 | 0.58 | | | |
| | 24 | | 3.15 | 5.07 | 0.62 | | | |
| | 27 | | 3.93 | 5.62 | 0.70 | | | |
| *Dicentrarchus labrax (67)* | 10 | | 1.13 | 4.46 | 0.25 | 0.64 | 0.16 | 0.48 |
| | 15 | | 2.03 | 4.95 | 0.41 | | | |
| | 20 | | 2.78 | 5.47 | 0.51 | | | |
| *Gobiodon erythrospilus (68)* | 29 | | 8.11 | 5.48 | 1.48 | 0.72 | 0.63 | 0.10 |
| | 31 | | 9.10 | 6.15 | 1.48 | | | |
| | 32 | | 9.94 | 6.41 | 1.55 | | | |
| | 33 | | 11.58 | 7.91 | 1.46 | | | |
| *Gobiodon histrio (68)* | 29 | | 6.29 | 4.78 | 1.32 | 1.23 | 0.84 | 0.38 |
| | 31 | | 9.31 | 5.63 | 1.65 | | | |
| | 32 | | 9.62 | 5.89 | 1.63 | | | |
| | 33 | | 12.04 | 8.04 | 1.50 | | | |
| *Paralichthys dentatus (69)* | 22 | | 1.41 | 5.67 | 0.25 | 0.69 | 0.35 | 0.33 |
| | 30 | | 2.88 | 8.19 | 0.35 | | | |
| *Scyliorhinus canicular (70)* | 7 | | 0.80 | 7.66 | 0.10 | 0.64 | 0.23 | 0.41 |
| | 12 | | 1.13 | 8.58 | 0.13 | | | |
| | 17 | | 1.90 | 10.83 | 0.18 | | | |
| *Squalus acanthias (71)* | 10 | | 0.79 | 3.33 | 0.24 | 0.61 | 0.21 | 0.40 |
| | 13 | | 1.26 | 3.24 | 0.39 | | | |
| | 17 | | 1.65 | 3.90 | 0.42 | | | |
| | 21 | | 2.03 | 4.37 | 0.46 | | | |
| | 23 | | 2.22 | 4.42 | 0.50 | | | |
| *Callinectes sapidus (72)* | 17 | | 1.20 | 3.57 | 0.34 | 1.04 | 0.45 | 0.59 |
| | 23 | | 1.80 | 4.20 | 0.43 | | | |
| | 28 | | 4.20 | 7.98 | 0.53 | | | |

| Table S2: Coatal Marine Animals continued | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Carcinus maenas (73)* | 7 | | 0.73 | 2.85 | 0.26 | 0.61 | 0.40 | 0.21 |
| | 15 | | 1.74 | 3.76 | 0.46 | | | |
| | 22 | | 2.93 | 8.03 | 0.36 | | | |
| *Chrysoblephus laticeps (74)* | 16 | | 2.42 | 4.62 | 0.52 | 0.66 | 0.42 | 0.24 |
| | 20 | | 3.56 | 5.90 | 0.60 | | | |
| | 24 | | 4.93 | 7.27 | 0.68 | | | |
| *Octopus vulgaris (75)* | 14 | | 2.16 | 4.57 | 0.47 | 0.77 | 0.30 | 0.47 |
| | 16 | | 2.80 | 5.10 | 0.55 | | | |
| | 18 | | 3.45 | 5.63 | 0.61 | | | |
| | 20 | | 4.20 | 6.14 | 0.68 | | | |
| *Lates calcarifer (76)* | 26 | | 2.81 | 3.36 | 0.84 | 0.58 | 0.22 | 0.36 |
| | 36 | | 5.81 | 4.41 | 1.32 | | | |
| *Tautogolabrus adspersus (77)* | 1 | | 0.66 | 3.55 | 0.19 | 0.38 | 0.22 | 0.16 |
| | 8 | | 0.99 | 4.49 | 0.22 | | | |

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