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Hormonal adjustments to future expectations impact growth and survival in juvenile fish

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Evolutionary ecology often studies how environmental factors define optimal phenotypes without considering the bodily mechanisms involved in their regulation. Here we used a dynamic optimisation model to investigate optimally concerted hormonal control of the phenotype. We studied a semi-realistic situation where hormonal control of appetite, metabolism and growth acts to prepare juvenile fish for an uncertain future with regard to food availability. We found a bottom–up effect in that hormone levels varied across environments and affected a range of phenotypic changes. We also describe a top–down effect as natural selection varied across environments, which affected evolutionary optimisation of hormone levels. These combined top–down and bottom–up effects produced a hormone-regulated phenotype that adjusted its foraging intensity and risk-taking in adaptive ways depending on the differences between current and expected long-term environmental conditions. Hence, understanding the response of these fish to their current conditions also requires an understanding of their future expectations. We found that when food availability was low, it was optimal for the juvenile fish to have low growth hormone, thyroid hormone and orexin levels, contrary to when food availability was high when these levels were higher. Individual variation emerged from the individually experienced food availability trajectories: Those that on average experienced higher food availability grew faster and had higher short-term mortality risk. They also had higher survival probability throughout the growth period. The opposite was true for individuals experiencing lower food availability. Hormonal mechanisms that often are overlooked by ecologists are thus important in the ultimate adaptive control of both behaviour and physiology, thereby impacting fitness through growth and survival.

Keywords: environmental variation, growth, hormone, preparation, strategy, survival

Introduction

Hormones are internal signalling molecules produced by endocrine glands and transported via the bloodstream. Together with the nervous system, they represent crucial mechanisms for controlling the functioning of the organism (Hiller-Sturmhöfel and

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Bartke 1998). In addition to influencing physiological processes, hormones can also affect the probability that a certain behaviour will happen (Nelson 2000), and variation in hormone levels can affect the solutions that organisms choose when faced with different tradeoffs, for example between the number and size of eggs (Zera et al. 2007).

Physiologists have traditionally focused on the proximate aspects of hormone regulation (Luck 2014) asking questions regarding 1) causation (detailing triggers and consequences from the organismal down to the molecular level) and 2) development (focusing on ontogeny and changes through life). But as pointed out by Tinbergen (1963), ultimate understanding of a behaviour and other biological traits also requires understanding of 3) the adaptive function or survival value and 4) evolutionary history (the trait's phylogeny). These two ultimate questions have been the focus of evolutionary ecologists, but traditionally little attention has been granted towards proximate mechanisms, like hormonal regulation. As pointed out by Lessells (2008), this difference in focus has led to a communication barrier and an increasing conceptual rift between the fields. More recently this has led to calls for a more holistic view, with studies aiming to bridge the gap (see for example Ricklefs and Wikelski 2002, Zera et al. 2007, Lessells 2008, McNamara and Houston 2009, Giske et al. 2013, Budaev et al. 2019). Without connections between proximate mechanisms and ultimate causation, physiologists may come to ignore the effects of evolutionary top–down control and co-adaptation of the hormone system, while ecologists may neglect important physiological mechanisms that prevent animals from what theory prescribes as optimal behaviour.

Here, we follow this perspective by considering growth in juvenile fish. Fish commonly grow continuously throughout life (Mommsen 2001), and large body size is in many cases necessary for a higher reproductive output, especially in females (Gross 2005). One major regulator of growth is the 'GH–IGF-1-axis', consisting of growth hormone-releasing hormone (GHRH), growth hormone–inhibiting hormone (GHIH), growth hormone (GH) and insulin-like growth factor 1 (IGF-1) (Robson et al. 2002). The thyroid hormones of the hypothalamic–pituitary–thyroid axis are also very important for growth, development and metamorphosis in fish (Power et al. 2001) through the regulation of energy use (Danforth and Burger 1984). To provide energy for growth and other processes, energy intake is controlled by the 'satiety hormone' leptin (Yan et al. 2016, Volkoff et al. 2017) and the 'hunger hormone' ghrelin (Dimaraki and Jaffe 2006, Rønnestad et al. 2017), with orexin neuropeptides also being important for appetite and food intake (Rodgers et al. 2002, Volkoff et al. 2005). The hormones mentioned represent only a subset of the many hormones that affect growth, development, metamorphosis and appetite of fish. The endocrine mechanisms controlling these processes are also highly interconnected with emerging properties that makes this system even more complex (Cowan et al. 2017).

Juvenile fish need to adjust their metabolic processes and behaviour, such as foraging, to grow to adult size with the highest possible survival. This is a difficult task because fish (as most other organisms) live in complex environments involving uncertainty. Therefore, they must accept some level of risk while foraging. If food for any reason gets scarce, foraging becomes harder and takes longer. How much time should a fish spend foraging during poor times, compared to when food is abundant and easily accessible? Should it wait for better times while drawing energy from its reserves? When is it time to stop waiting and start rebuilding those reserves? These are all questions that involve processes mediated by hormones. It also implies that, somehow, hormones have evolved to regulate the organisms' adaptive responses to multiple tradeoffs, in the light of consequences over multiple timescales. We aimed to understand this using a dynamic optimisation approach that finds the optimal solution to an evolutionary problem through fitness maximisation. Using backward induction, the algorithm works backwards in time, from the end to the beginning of the selected study period, always choosing what is best in the current time step (Mangel and Clark 1988, Clark and Mangel 2000). Even if dynamic optimisation cannot reveal the intermediate steps along the evolutionary trajectory, it can point to the optimal end-result. Here we use one such optimisation model designed to study how hormones and combinations of them can integrate bioenergetics and survival through their consequences for Darwinian fitness and adaptive traits (Weidner et al. 2020).

Using a simplified version of the hormone system regulating growth, metabolism and foraging activity, Weidner et al. (2020) studied the optimal hormone levels in growing juvenile fish under differing levels of constant food availability. Hormonal axes and signalling molecules were combined into 'hormone functions', based on their physiological effects: 1) 'the growth hormone function', 2) 'the thyroid hormone function' and the 3) 'orexin function', representing the GH–IGF1-axis, thyroid-axis and the hormones and neuropeptides affecting appetite, respectively. The model revealed that evolutionarily optimal hormone regulation in constant environments depends on the food availability. Fish living in environments with higher food availability had higher optimal hormone function levels than other fish, resulting in higher food intake, metabolism and growth.

Using the model of Weidner et al. (2020), we have in this study moved the focus of the optimal policy from the endpoint (behaviour), not all the way to the starting point (genes), but to some midpoint (hormone system), where behaviour and thereafter growth and survival become consequences of evolutionary optimisation. We have investigated how hormones and combinations of them might prepare the phenotype for changes in a fluctuating environment. How can temporal changes in the environment affect behaviour and growth, when responses to such changes are mediated by hormones? And what is the optimal response of the hormone system given the tradeoff that fish encounter in a varying environment?

Methods

We have studied the effects of hormones and the combinations of them for adaptive growth strategies of juvenile fish when food availability varies stochastically over time around an expected mean. The model follows the energy flow through the fish, from foraging, digestion, metabolic costs of maintenance and activity, to growth. The fish has energy reserves it may draw from in times of scarcity and replenish when conditions allow. Because part of our aim is to bridge the gap between proximate and ultimate explanations for growth, the modelled individuals face several tradeoffs between energetics and survival affected by their hormone strategy. We give a brief outline of the model below and refer to the Supplementary material Appendix 1 and Weidner et al. (2020) for details. The extension in this model version replaces the constant food environment in Weidner et al. (2020) with an environment where food availability varies stochastically through time.

To make the model tractable (Hilborn and Mangel 1997), we simplified the full complexity of the hormone system into three sets of hormone functions, which we refer to as such, to distinguish them from real molecules (Weidner et al. 2020). First, the growth hormone function (GHF) controls growth, which we assume is isometric. As mortality decreases with size, GHF has the potential to affect the future mortality risk of the fish, and thus its survival probability at the end of the growth period. Second, the orexin function (OXF) controls the appetite of the fish, and thus its foraging activity. As fish that spend more time foraging cannot spend as much time hiding from predators, short-term mortality risk increases during foraging activities. Finally, the thyroid hormone function (THF) affects the physiology and mortality risk of the fish in two ways: on one hand, it increases maximum oxygen uptake, which makes it easier to escape predators. On the other hand, it increases metabolism and thereby energy and oxygen demand, which in turn necessitates more foraging and thus higher exposure to predators. A central assumption in the model is that respiratory constraints mediate important links between energetics and survival. This approach builds on Priede (1985) and experimental results from Atlantic silversides *Menidia menidia*, where fast-growing fish not only ate more, but were also predated more often (Billerbeck et al. 2001, Lankford et al. 2001). Following Holt and Jørgensen (2014) that extended Pörtner's (2010) oxygen and capacity-limited thermal tolerance theory to a fish life history model, we model this by considering all aerobic metabolic processes and comparing the total oxygen consumption to the maximum oxygen uptake. The more oxygen is used, including oxygen use by physiological processes such as digestion and growth, the more vulnerable the fish is to be captured by a predator it encounters. Our model thus includes several common tradeoffs which are all affected by the hormone function levels.

It should be noted that the hormone function levels in our model have clear ecological interpretations. The levels of GHF and THF for example frequently falls to zero under poor conditions. This does not mean that the animal is experiencing fatally low GHF and THF levels, however: If the GHF levels in the model simulations are zero, the fish simply does not grow. Similarly, when THF levels drop to zero this means that the metabolism is reduced to low levels where the fish has little capacity to escape predators as it saves energy but can still support life-sustaining processes.

We used dynamic programming (Mangel and Clark 1988, Clark and Mangel 2000) to optimise hormone strategies. This method finds the optimal combination of the hormone functions that yields the highest survival throughout the fish' juvenile growth phase. The algorithm works backwards in time, and for every combination of the three states length, reserve fullness and current food availability, it finds the combined hormone strategy that maximises survival in the current time step and the future. After finding the state-dependent optimal combination of the hormone functions, we simulate individual trajectories of juvenile fish that follow the optimal hormone strategy as they grow. Because the environment varies stochastically, each individual experiences different food availabilities over time. These differences bring about individual variation in physiological state and optimal hormone tactics.

In Weidner et al. (2020), the food availability E [dimensionless] was kept constant, while in this extension of the model, food availability varies stochastically over time. In nature food availability usually does not vary independently from one day to the next, and E is, therefore, autocorrelated over time (Fig. 1a). In this model, fish cannot migrate; only respond to food availability changes by adjusting their hormone profile and thereby energy acquisition and use. Still, even if food availability is poor, fish can always find food, but need to spend more time and energy to do so, at the cost of increased predator exposure (Weidner et al. 2020, Supplementary material Appendix 1).

Food availability follows a normal distribution, and intermediate food availability therefore occurs more frequently than rich and poor. To find E in week t ($E(t)$), we use an autocorrelated process modified from Ripa and Lundberg (1996):

$$E(t) = k_{\mathrm{E\_sd}} \times \left[E(t-1) \times k_{\mathrm{E\_autocorr}} + \mathrm{normal}(0,1) \times \sqrt{1 - k_{\mathrm{E\_autocorr}}^2} \right] + 1,\ E \in \left[E_{\min}, E_{\max} \right]$$

Here $E(t-1)$ is the relative food availability (where the average is 1) in the previous time step, normal(0,1) is a random number drawn from a standard normal distribution and $k_{\mathrm{E\_autocorr}}$ is the autocorrelation constant. For $k_{\mathrm{E\_autocorr}} = 1$ food availability is constant, while $k_{\mathrm{E\_autocorr}} = 0$ results in a current food availability that does not depend on the previous food level. We consider a scenario where $0 < k_{\mathrm{E\_autocorr}} < 1$ and food availability is positively autocorrelated between time steps. The width of the distribution is determined by its standard deviation, $k_{\mathrm{E\_sd}}$. When implemented, the distribution is capped between $E_{\min}$ and $E_{\max}$, representing the poorest and richest food availability, respectively.

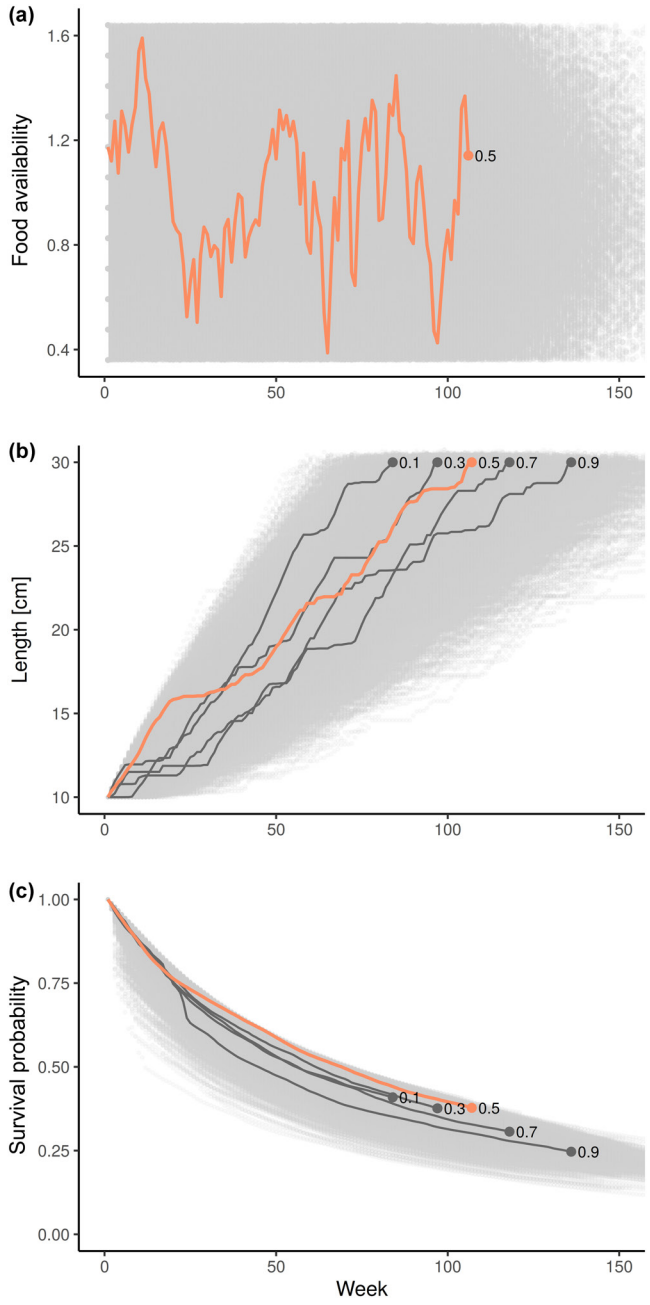

Figure 1. Trajectories of individuals with different experiences of food availability during their growth period. The grey points are raw data for the whole population of 10 000 individuals. (a) Food availability trajectory for the median (i.e. 0.5 quantile) individual of the population in terms of growth speed illustrates the temporal variation in the model. (b) The growth rate for individuals representing the 0.1, 0.3, 0.5, 0.7 and 0.9 quantile in terms of growth speed. (c) Variation in survival probability for the same individuals as in (b).

Simulations

The effect of the variable environment was compared against constant environments. To do this, we simulated 10 000 individuals with stochastic food availability (variable environment). Additionally, we conducted 12 simulations with constant food availability (constant environment) using 12 levels of food availability at equal intervals within the range of the variable environment simulations. As there was a single optimal strategy in each constant environment, we simulated one fish per environment. Except for the variable or constant environment, the simulations were in all other ways equal. Initial starting length of the fish was 10 cm, and max length for the simulation was set at 30 cm. We then compared the results from these 13 simulations when individuals were 20 cm in length. The variable environment was run for 250 weeks, and all individual fish were able to reach 30 cm within this time. As the constant environments only were used for comparisons, these simulations were run until the fish reached 20 cm, which took up to 284 weeks in the poorest environment.

By simulating individuals in different situations, we investigated how hormonal mechanisms result in differences in growth and survival of the organism. To study this more in detail, we focused on three individual fish that were optimised towards the variable environment. We let these fish experience identical trajectories of food availability until they reached 20 cm, and then simulated either of three levels of food availability: 1) rich, 2) intermediate and 3) poor, that were all within the food availability range the fish were optimised for. This procedure provided an equivalent to experimental manipulation.

Results

Let us first point out that all our results derive from a model that maximises total survival throughout a period of growth as a proxy for fitness, where the bioenergetics to fuel growth and behavioural risk-taking are the key components. Thus, the model explains how hormones can produce a phenotype that best grows to maximise survival through the juvenile phase of a fish. As food availability is changing over time with stochastic fluctuations (Fig. 1a), each fish has its own historical growth trajectory. Those that on average were lucky experienced more profitable food conditions and grew faster, while the less fortunate grew more slowly (Fig. 1b). Food availability also affected the survival probability of individuals (Fig. 1c). Most of the results that follow summarise the information from such individual trajectories of physiology, growth and survival.

Optimal hormone strategies depend both on the current and the expected conditions

Optimal hormone levels were dynamic in ways that considered both the present state of the environment and how it is likely to change in the near future. The modelled fish did not know their future environment, but the dynamic programming method to find the evolutionarily optimal policy considered the current state of the environment as well as the long-term expected average. In variable environments, it was

optimal for fish to increase hormone function levels when food availability was high. This led fish to escalate their intake (and thus energy surplus) and accept more risks to grow faster compared with fish that lived in a constantly rich environment (diamonds versus circles in Fig. 2). During poor food conditions, fish in variable environments decreased hormone function levels to save energy and reduce activity and growth. As a consequence, they had lower foraging related mortality relative to fish living under constantly poor food conditions (Fig. 2b–c). The plastic up and down regulation of hormone function levels in variable environments resulted in fish managing growth and predation risk dynamically though their juvenile phase.

The simplest future expectation is that the current condition will persist. Fish in constant environments therefore had no need for carrying reserves as an insurance against future uncertainty (Weidner et al. 2020). In contrast, optimal hormone policies for fish in variable environments secured reserves and adjusted their levels to avoid starvation during periods of food shortage (Fig. 2). Generally, reserves are built when OXF levels signal increased appetite for food while GHF levels are low, so the digested energy is not spent on growth (Fig. 2). The reserves can be metabolised and spent during food shortage, and combined with low GHF to cut expenditures, this permits low OXF levels that reduce risky foraging.

Individual variation emerges from environmental stochasticity

To illustrate what happens when food availability changes, we ran three fish through an identical food availability trajectory before letting them experience conditions with rich, intermediate or poor food availability when they reached a length of 20 cm (Fig. 3). It was optimal for an individual to boost hormone function levels during rich feeding conditions (red line with diamonds in Fig. 3a): High GHF sustained growth, high OXF provided food and high THF improved survival while foraging. Conversely, lower hormone function levels were observed in poor periods to reduce activity and to save energy, which thus reduced encounters with predators while waiting for the food availability to improve (blue line with triangles in Fig. 3a). This reflects how it is optimal for a juvenile fish in a variable environment to act as if the experienced food availability is only temporary; by increasing feeding when it is rich and await better times when it is poor. This is comparable to the 'take-it' tactic described by Wingfield and Kitaysky (2002). In constantly poor environments, these considerations are different; fish had high optimal OXF levels and thus, continued to forage actively despite high risk as conditions could not be expected to improve (Fig. 2b).

One way to think of ultimate top–down control in variable environments is that fitness always puts a premium on growth, but that only certain conditions permit growth to take place with reasonably high survival. When food availability was high, it was optimal for fish to increase GHF levels, which increased energy demand (Fig. 3a) and in turn

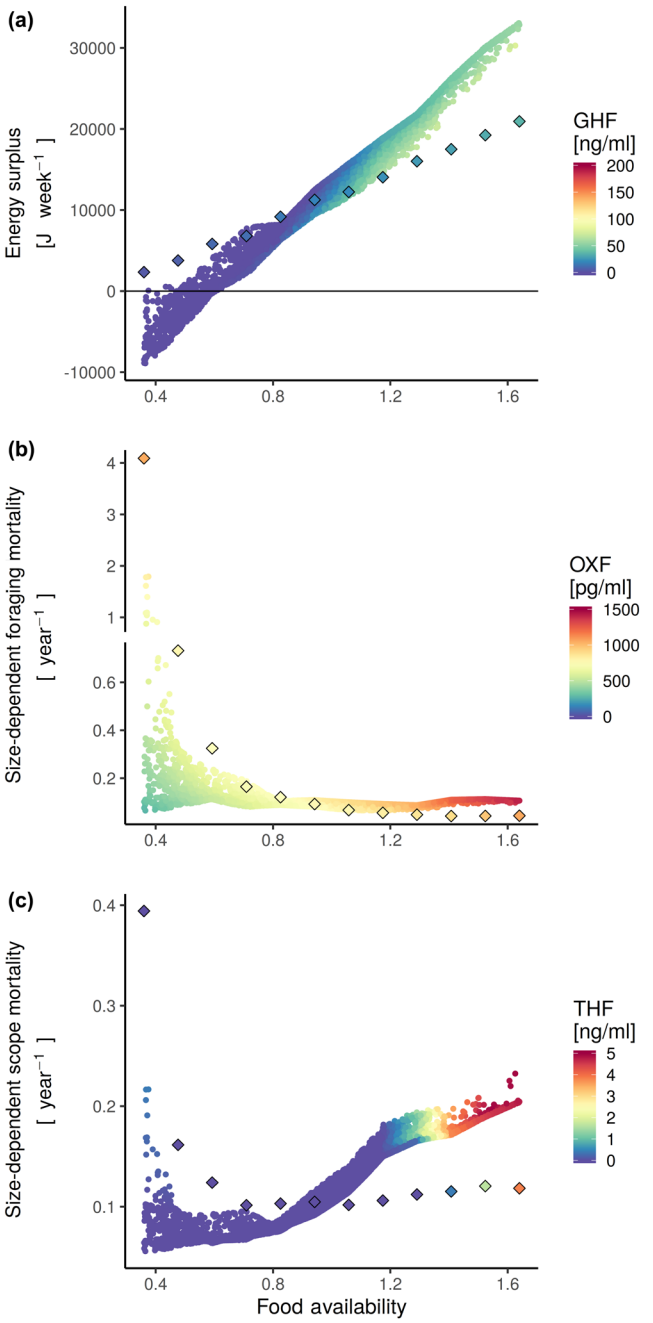

Figure 2. Energy surplus, mortality rate and optimal hormone levels for different food availabilities, for fish at 20 cm in length. Each point represents an individual. The diamonds (◊) represent twelve simulations with constant food availability. (a) Energy surplus [J week^{-1}] (energy left of intake after metabolism, digestion and activity costs are accounted for) under differing food availabilities, with growth hormone function (GHF) strategy as colour. (b) The size-dependent foraging mortality rate under differing food availabilities and orexin function (OXF) concentrations. (c) The size-dependent scope mortality rate under differing food availabilities and thyroid hormone function (THF) levels.

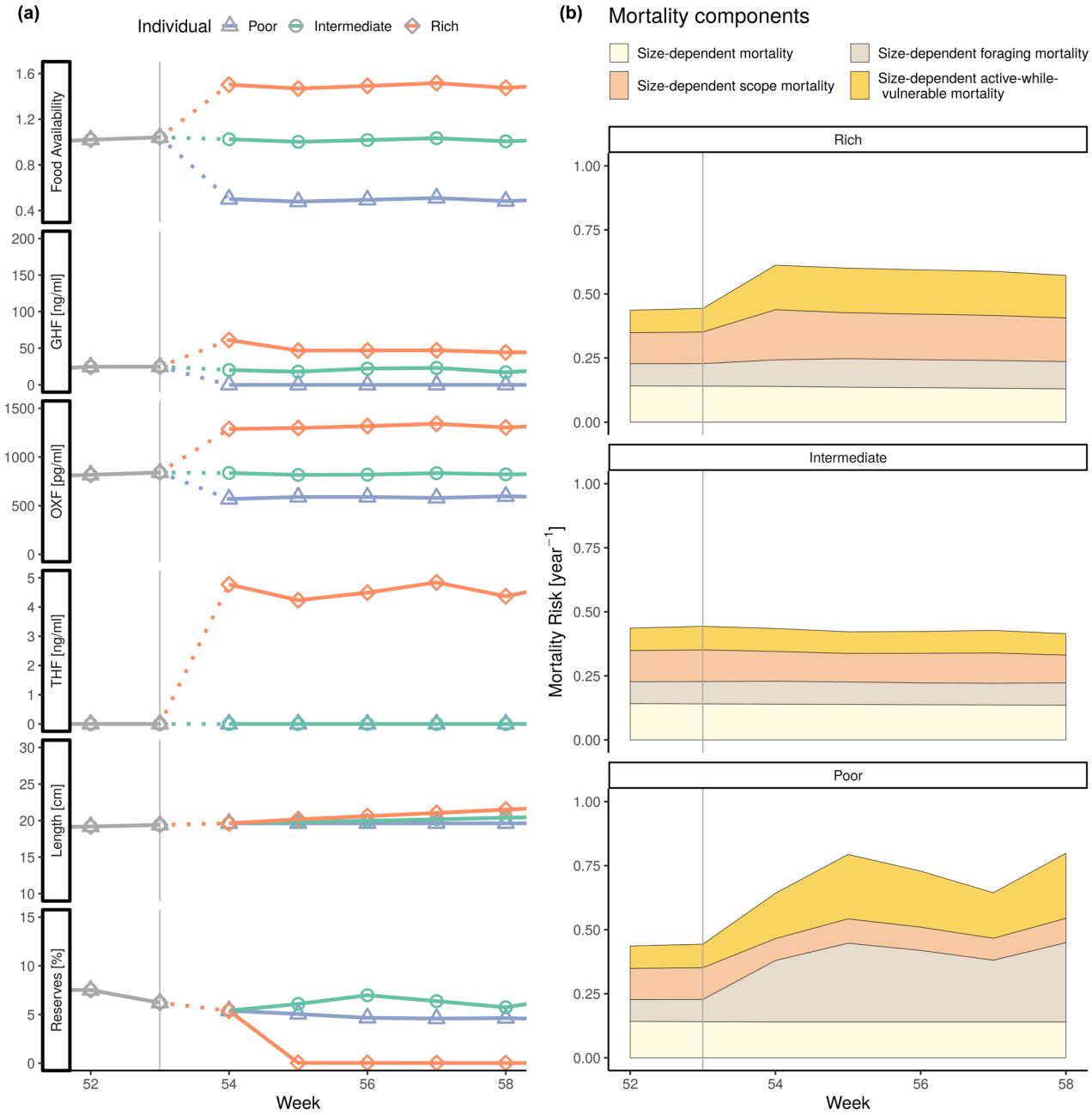

Figure 3. Food availability as the driver of optimal hormone profile variation. Three individuals with identical hormone strategies optimised towards the same autocorrelated food availability regime was set to experience identical food regimes until they reached 20 cm, and thereafter three different levels, all well within the environmental variation they were optimised towards. (a) The realised hormone trajectories consisting of the growth hormone function (GHF), the orexin function (OXF) and the thyroid hormone function (THF) and the resulting phenotype represented by length and reserve fullness. (b) The mortality risk experienced by the three individuals, and its components. Size-independent mortality is removed from the legend as it had a stable rate of 0.01 per year.

required a higher food intake. It was thus optimal to increase OXF levels to upregulate foraging activity. To sustain several metabolically demanding processes concurrently also required high THF levels. High food availability permitted efficient foraging, which provided the energy to sustain high THF levels, that in turn reduced vulnerability to predation (Fig. 3). When food availability was low, the optimal tactic involved a very different hormone profile with low GHF, THF and OXF levels. Only when facing immediate death due to starvation, the OXF and THF levels were increased (Fig. 2).

As a result, the risk of mortality increased both for individuals experiencing a change to poor and to rich food availability compared to those experiencing intermediate food

availability (Fig. 3b). When food availability was high, the size-dependent scope and the size-dependent active-while-vulnerable mortalities increased due to higher foraging activity following increased OXF levels. (The active-while-vulnerable component represents an interaction between the size, foraging and scope mortality components, for more details see Weidner et al. (2020) and the Supplementary material Appendix 1) This occurred because the fish had a higher metabolism due to increased THF levels (red lines in Fig. 3a), and higher oxygen use due to higher foraging activity and metabolic processes that convert food to growth. The link to fitness is that individuals used THF primarily to decrease their vulnerability to predation by increasing their threshold for maximum oxygen uptake (Fig. 2c, 3b).

When desperate, gamble

There is an important exception to the general rule of higher hormone function levels when the food availability is rich and lower levels when it is poor: If conditions in the past had been so bad that the fish faced immediate death due to starvation, it became beneficial to increase OXF and THF levels even if food availability remained poor (Fig. 2). The increase in hormone function levels led to higher foraging activity (Fig. 2), with a short-term elevation of predation risk. The tactic could lead to a quicker death by predation than had the fish just waited to die by starvation, but there is a chance that increased foraging activity could save its life. This desperate hormone tactic was only optimal for individuals facing immediate risk of dying due to starvation, as their reserves otherwise were expected to continue to decrease (Stephens 1981).

Growth and survival as consequences of environment-sensitive hormone strategies

While it is common to express feeding and growth from hormone dynamics, we also found clear effects of hormones on mortality risk: the model assumes that foraging mortality decreases with feeding activity, but when individuals experienced high food availability instantaneous mortality risk was higher (Fig. 4a). The fish lived as if good times could not be expected to last and it was therefore optimal to increase OXF levels to prioritize energy intake when food was abundant. This hormone-driven shift in behaviour resulted in higher mean mortality risk for individuals that most of the time experienced rich food availability (Fig. 2b, 3, 4b). Due to the higher GHF levels (Fig. 2a, 3a), these individuals however, grew faster and thus had a higher probability of surviving the juvenile growth period (Fig. 4c). In contrast, fish that by chance lived most of the time under poor food availability, experienced lower mean mortality risk, but slower growth led to lower survival probability.

The dependency of optimal policy on food availability made fish build reserves at levels of intermediate food availability (Fig. 5a, c). These reserves served two purposes: they were used for growth when food availability was high and to

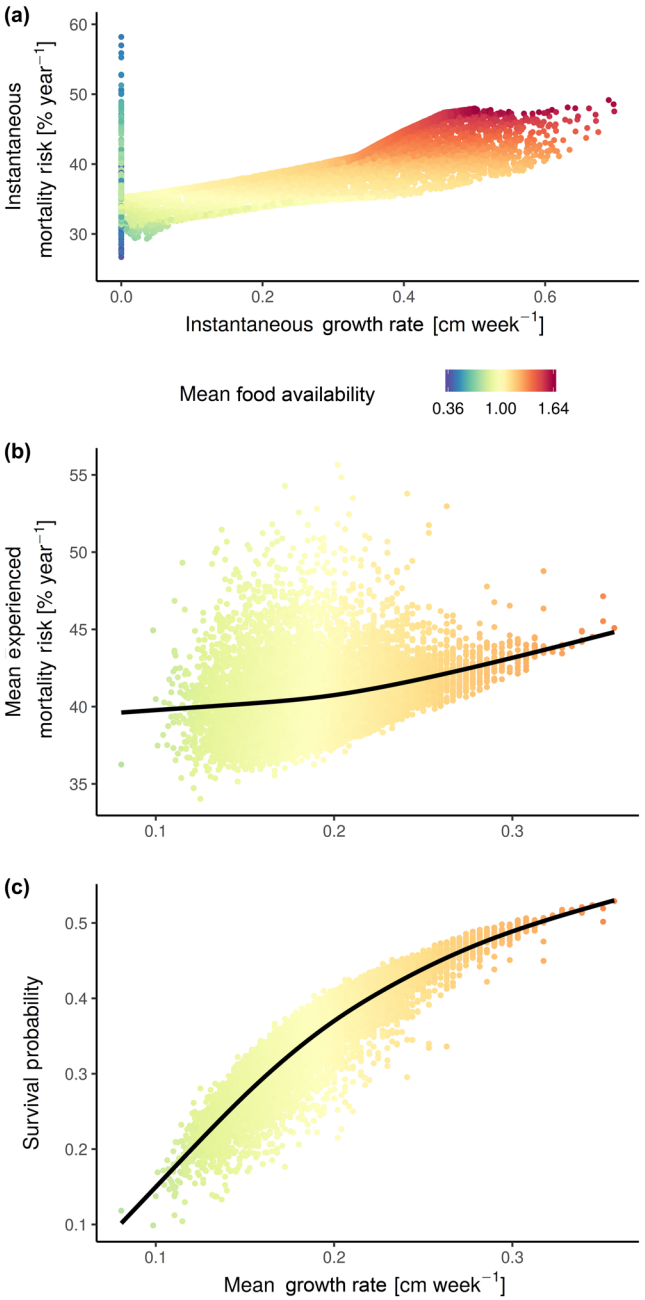

Figure 4. Mortality risk and growth rate for fish in an environment with varying food availability. Each point represents an individual fish. The mean food availability experienced by the individual is represented by the colour of the point. (a) Instantaneous mortality risk [% year^{-1}] and growth for one week (= one model time step) when the model fish was around 20 cm. (b) Mean experienced mortality risk per year [% year^{-1}] and mean growth rate [cm week^{-1}] for every fish during growth from 10 to 30 cm. (c) Survival probability at the end of the growth period and mean growth rate for each individual fish. Lines for (b) and (c) are fitted using a generalised additive model (GAM) for illustrative purposes.

avoid starvation when conditions were poor (Fig. 5). When food availability was high, use of reserves was primarily connected to higher GHF and THF levels. This led to higher energy demand from both growth and metabolism (Fig. 2a, c, 3a). Under poor food availability, fish could not afford this luxury and OXF became more important (Fig. 2b, 3a) for keeping intake and reserves at levels that avoided starvation (Fig. 5b–c). Around intermediate levels of food availability, intermediate levels of OXF and low levels of GHF and THF (Fig. 2, 3a) led to a high net energy intake that was used to build reserves (Fig. 5c).

Discussion

Using an evolutionary optimisation model, we have found that stochastic environments promote dynamic hormone levels, energetics and growth. Under high food availability, it was optimal to boost hormone function levels, while suppressing them under poorer food conditions. When poor feeding conditions persisted until the fish faced immediate risk of death due to starvation, the best strategy was to gamble by increasing the hormone function levels affecting foraging and mortality risk, even when this came at the cost of increased predation risk. We found that the optimal plastic response of the hormone system is dependent on both food availability, as well as the level of variability in the environment. Thus, the hormone system maintains and adjusts a flexible phenotype, so that top–down control from evolutionary adaptation of the hormone system integrates both bioenergetics and survival in ways that maximise fitness.

Most hormones interact in complex ways with other hormone functions and have widespread and diverse effects on an organism's physiology and behaviour. The three hormone functions in this model are very simplified relative to natural fish. The environment is also reduced to just a single factor, varying food availability, with no competition among individuals. Even though our model is necessarily a simplification, general trends in the hormone regulation still seem to match the patterns found in nature (Weidner et al. 2020). For example, facing starvation (but not immediate death) tends to cause decreased thyroid hormone levels in mammals, birds and fish (Eales 1988). Starved rats produce less of both growth hormone and thyroid stimulating hormone (Armario et al. 1987).

Because of the simplified and partially predictable nature of our model environment, individuals can nearly drain their reserves when food availability is high. Natural organisms, in contrast, are adapted to various unpredictable events (e.g. disease, predators, changes in social status) which should require larger energy reserves (Wingfield and Kitaysky 2002). It is, however, reasonable to assume that organisms living in predictable and rich environments may need smaller reserves than those living in less predictable environments. It is also worth noting that we have presented results from only one level of environmental variation, and that food availability in natural environments could be more or less predictable,

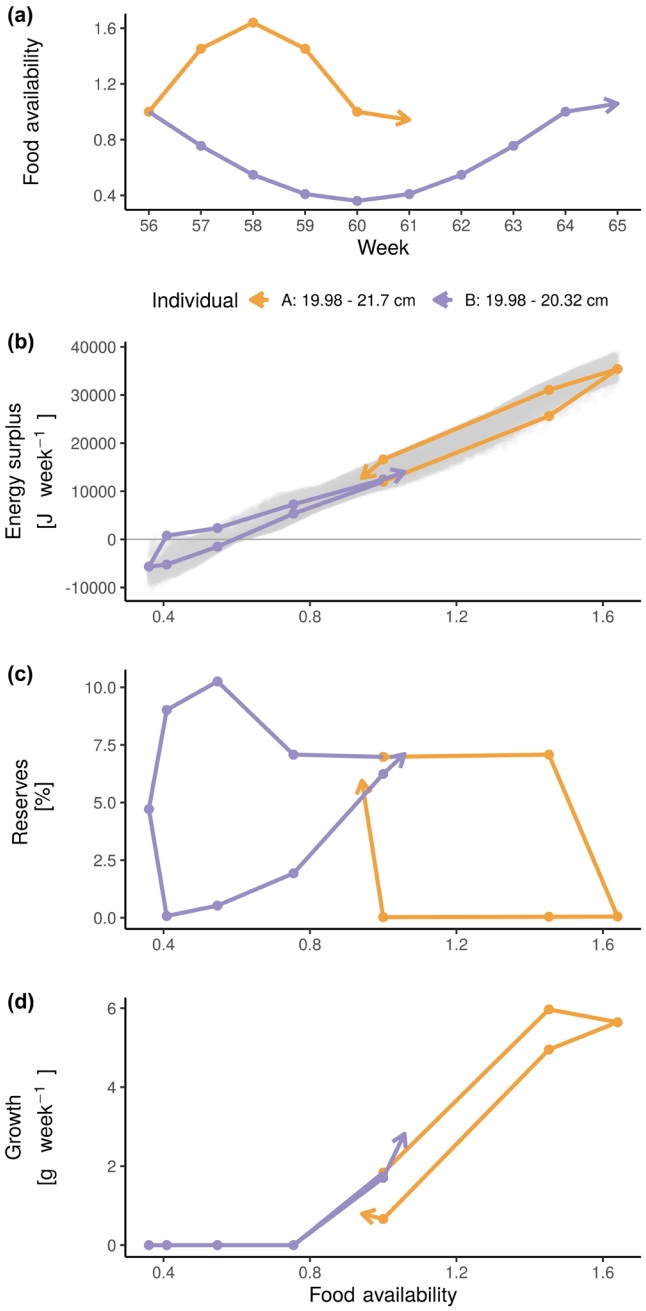

Figure 5. Energy use under different food availabilities illustrated with trajectories of two individuals. (a) The food availabilities that the two individuals were subjected to for the purpose of this illustration. (b) When the food availability increases, the individuals first use their reserves to grow before they increase their relative surplus before growth (J) (energy left of intake after metabolism, digestion and activity costs are accounted for). (c) Individuals primarily build up their reserves when they experience average food availability. Under high food availability, they use their reserves to grow, while under poor food availability the reserves are used to stay alive until the food availability improves. (d) Individuals primarily grow when the food availability is around average to high.

which should affect the strategies of the organisms living there (Higginson et al. 2012).

Natural environments vary in terms of resource availability. Such variability typically has both predictable (e.g. seasonal or diurnal) and unpredictable (i.e. stochastic) components. Organisms have therefore evolved ways to increase their energy intake in variable environments (Pyke et al. 1977). They also employ plastic strategies, making use of certain tactics under specific environmental conditions (Gotthard and Nylin 1995). When encountering unpredictable events like a drastic decrease in food availability, organisms can respond with an 'emergency life history stage'. It is often characterised by three different behavioural and physiological tactics (Wingfield and Kitaysky 2002): 1) 'leave-it' where the individuals moves to a different environment, 2) 'take-it' where the individual switches to energy conservation, but remains in the environment or 3) a combination of the two where individuals first 'take-it' and then 'leave-it' should conditions fail to improve. These tactics are likely orchestrated in large part by the endocrine system in response to both current and expected environmental conditions.

The hormonal dynamics seen in this model can illuminate some of the dynamics involved in compensatory growth. Several studies have observed that animals deprived of food for some time can thereafter compensate with a period of higher feeding and growth rates (Wilson and Osbourn 1960, Ali et al. 2003), even at increased short-term risk of mortality (Dmitriew 2011) or disease (DeBlock and Stoks 2008). Fish in our model did not have the option to leave their environment at times of low food availability. But instead of just 'taking it' we saw that they employed a dynamic hormone strategy that depended on the temporal variation of the environment. These results are in line with what Lima and Bednekoff (1999) found for optimal anti-predator behaviour in environments alternating between periods of high and low risk. They argued that if the high-risk situations were brief and infrequent, an animal should feed primarily in the low-risk situation and employ the greatest level of anti-predator avoidance in the high-risk situation. Lima and Bednekoff (1999) also found that if the high-risk situation was prolonged, the animal should feed also in high-risk situations to avoid starvation mortality. We observed a similar behavioural response in unlucky fish that experienced low food availability for a prolonged period. Our model, however, adds an additional layer of insight by coupling these behaviours with underlying physiological mechanisms.

In our model, fish adjusted foraging and predation risk through plastic hormone functions. Under rich food availability, they used their reserves for growth, under intermediate conditions they grew less and built reserves, while under the poorest conditions they did not grow and used their reserves to survive. This resulted from the main optimal policy: increase hormone functions levels with food availability. Hormone levels have often been found to vary seasonally (White and Henderson 1977, Marchant and Peter 1986, Bubenik et al. 1998), and this has often been seen in connection with temperature and day length. In white groupers *Epinephelus aeneus* in Suez Gulf in Egypt, triiodothyronine (T_3) and thyroxine (T_4) levels were found to increase during spring and summer, peak during midsummer and decrease during autumn and early winter, before increasing again (Abbas et al. 2012). The hormone levels were not only connected to temperature, but also to increased growth and food assimilation, which coincided with the peak in T_3 and T_4 levels (Abbas et al. 2012). This is consistent with our results, where THF, growth (GHF) and foraging (OXF) increased during periods of high food availability. Even though this was not linked with physiological preparation by Abbas et al. (2012), the seasonal variation in hormone levels probably represents an evolved hormone strategy that helps organisms anticipate and shift energy and mortality costs adaptively over the year and during their life-history. This brings our model closer to the predictive decision perspective (Budaev et al. 2019).

One of our results concerns how differences in the experienced environment bring about individual differences in mortality risk and growth rate, which is a much-studied tradeoff (Werner and Gilliam 1984, Mangel and Stamps 2001). Treatments with growth hormone increased growth rate but reduced the anti-predation response in juvenile brown trout *Salmo trutta* because of increased energy demands (Johnsson et al. 1996). The same tradeoff between growth and mortality was also found in growth hormone transgenic Atlantic salmon *Salmo salar* (Abrahams and Sutterlin 1999, Sundström et al. 2004), and transgenic channel catfish *Ictalurus punctatus* containing salmonid growth hormone genes (Dunham et al. 1999). In our model, the fastest growing individuals forage more, because of high OXF levels, and have on average higher GHF levels, and as result of this they experience higher short-term mortality risk. Because of faster growth rate, however, their overall expected survival throughout the juvenile phase is higher. This is consistent with studies that have looked at the link between resources and growth rates (Hentschel 1999). Our model is thus able to represent the tradeoff between mortality and growth, the trade-off between resource availability and growth, as well as the tradeoff between resource availability and survival (Fisher 1930, Stearns 1989, Zera and Harshman 2001). Since the food availability in our model is variable, it also highlights that individual differences in growth rate can be explained in part due to chance.

Our results show that hormones can be considered as both specific physiological entities and functional units that mediate top–down changes in organisms regarding growth, survival and reproduction. Yet, there are also concerted regulations of the phenotype across levels like genes (Biscontin et al. 2019), emotion (Giske et al. 2013, Andersen et al. 2016) and cognition (Budaev et al. 2019), and these levels also interact. When testing predictions of this model empirically, it is important to focus on the general patterns found in the hormone functions rather than specific numerical values as these might vary from species to species. The hormone functions are made to

reflect changes in hormone systems, but they can also be compared to changes in the end hormones IGF-1 (GHF) and T_3 (THF), as well as the neuropeptide orexin-A (OXF).

An interesting difference between this paper and the same model used in a stable environment (Weidner et al. 2020) is the active role of the hormone system in the preparation of the phenotype for what is expected to come. This would have been even more pronounced if the model environment also had been seasonal (Stefansson et al. 2008). Hence, full understanding of the hormone system should include not only the past and the present state of the animal and its environment, but also the expected future. Indeed, one evolutionarily top–down effect of the hormones is to prepare the animal for the most likely change. Fish, insects and many other kinds of animals have another tool for future planning – the nervous system – that controls motivation, emotion, learning and cognition (Budaev et al. 2019). The hormonal, nervous and cognitive systems are involved in making predictions and responding to the expected future at different time scales. The animal is more complex than just a stimulus–response machine: it is agentic (Dickinson 1985, Bubic et al. 2010, Clark 2013, Budaev et al. 2019) and behaves according to its subjective expectations to future conditions (Higginson et al. 2012). This has implications for how to conduct and interpret laboratory experiments. The hormone system is likely an important component of this prediction machinery.

Data availability statement

The source code for the model is available from Zenodo: <https://doi.org/10.5281/zenodo.4005943> (Jensen et al. 2020). Data can be generated by using the parameters supplied in the Supplementary material Appendix 1.

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References

Abbas, H. H. et al. 2012. Effect of seasonal temperature changes on thyroid structure and hormones secretion of white grouper (*Epinephelus aeneus*) in Suez Gulf, Egypt. – Life Sci. J. 9: 700–705.
Abrahams, M. V. and Sutterlin, A. 1999. The foraging and antipredator behaviour of growth-enhanced transgenic Atlantic salmon. – Anim. Behav. 58: 933–942.
Ali, M. et al. 2003. Compensatory growth in fishes: a response to growth depression. – Fish Fish. 4: 147–190.
Andersen, B. S. et al. 2016. The proximate architecture for decision-making in fish. – Fish Fish. 17: 680–695.
Armario, A. et al. 1987. Chronic food restriction and the circadian rhythms of pituitary–adrenal hormones, growth hormone and thyroid-stimulating hormone. – Ann. Nutr. Metab. 31: 81–87.
Billerbeck, J. M. et al. 2001. Evolution of intrinsic growth and energy acquisition rates. I. Tradeoffs with swimming performance in *Menidia menidia*. – Evolution 55: 1863–1872.
Biscontin, A. et al. 2019. Analysis of the circadian transcriptome of the Antarctic krill *Euphausia superba*. – Sci. Rep. 9: 13894.
Bubenik, G. A. et al. 1998. Seasonal levels of metabolic hormones and substrates in male and female reindeer (*Rangifer tarandus*). – Comp. Biochem. Physiol. C Pharmacol. Toxicol. Endocrinol. 120: 307–315.
Bubic, A. et al. 2010. Prediction, cognition and the brain. – Front. Hum. Neurosci. 4: 25.
Budaev, S. et al. 2019. Decision-making from the animal perspective: bridging ecology and subjective cognition. – Front. Ecol. Evol. 7: 164.
Clark, A. 2013. Whatever next? Predictive brains, situated agents and the future of cognitive science. – Behav. Brain Sci. 36, 181–204.
Clark, C. W. and Mangel, M. 2000. Dynamic state variable models in ecology: methods and applications. – Oxford Univ. Press.
Cowan, M. et al. 2017. Rhythms in the endocrine system of fish: a review. – J. Comp. Physiol. B 187: 1057–1089.
Danforth, E. and Burger, A. 1984. The role of thyroid hormones in the control of energy expenditure. – Obesity 13: 581–595.
DeBlock, M. and Stoks, R. 2008. Short-term larval food stress and associated compensatory growth reduce adult immune function in a damselfly. – Ecol. Entomol. 33: 796–801.
Dickinson, A. 1985. Actions and habits: the development of behavioural autonomy. – Phil. Trans. R. Soc. B 308: 67–78.
Dimaraki, E. V. and Jaffe, C. A. 2006. Role of endogenous ghrelin in growth hormone secretion, appetite regulation and metabolism. – Rev. Endocr. Metab. Disord. 7: 237–249.
Dmitriew, C. M. 2011. The evolution of growth trajectories: what limits growth rate? – Biol. Rev. 86: 97–116.
Dunham, R. A. et al. 1999. Predator avoidance of transgenic channel catfish containing salmonid growth hormone genes. – Mar. Biotechnol. 1: 545–551.
Eales, J. G. 1988. The influence of nutritional state on thyroid function in various vertebrates. – Am. Zool. 28: 351–362.
Fisher, R. A. 1930. The genetical theory of natural selection. – Clarendon Press.
Giske, J. et al. 2013. Effects of the emotion system on adaptive behavior. – Am. Nat. 182: 689–703.
Gotthard, K. and Nylin, S. 1995. Adaptive plasticity and plasticity as an adaptation: a selective review of plasticity in animal morphology and life history. – Oikos 74: 3–17.
Gross, M. R. 2005. The evolution of parental care. – Q. Rev. Biol. 80: 37–45.
Hentschel, B. T. 1999. Complex life cycles in a variable environment: predicting when the timing of metamorphosis shifts from resource dependent to developmentally fixed. – Am. Nat. 154: 549–558.
Higginson, A. D. et al. 2012. Generalized optimal risk allocation: foraging and antipredator behavior in a fluctuating environment. – Am. Nat. 180: 589–603.
Hilborn, R. and Mangel, M. 1997. The ecological detective: confronting models with data. – Princeton Univ. Press.

Hiller-Sturmhöfel, S. and Bartke, A. 1998. The endocrine system: an overview. – Alcohol Health Res. World 22: 153–164.
Holt, R. E. and Jørgensen, C. 2014. Climate warming causes life-history evolution in a model for Atlantic cod (*Gadus morhua*). – Conserv. Physiol. 2: 1–16.
Jensen, C. H. et al. 2020. Hormone model stochastic. – Zenodo, <https://doi.org/10.5281/zenodo.4005943>
Johnsson, J. I. et al. 1996. Domestication and growth hormone alter antipredator behaviour and growth patterns in juvenile brown trout, *Salmo trutta*. – Can. J. Fish. Aquat. Sci. 53: 1546–1554.
Lankford, T. E. et al. 2001. Evolution of intrinsic growth and energy acquisition rates. II. Tradeoffs with vulnerability to predation in *Menidia menidia*. – Evolution 55: 1873–1881.
Lessells, C. M. 2008. Neuroendocrine control of life histories: what do we need to know to understand the evolution of phenotypic plasticity? – Phil. Trans. Biol. Sci. 363: 1589–1598.
Lima, S. L. and Bednekoff, P. A. 1999. Temporal variation in danger drives antipredator behavior: the predation risk allocation hypothesis. – Am. Nat. 153: 649–659.
Luck, M. 2014. Hormones: a very short introduction. – Oxford Univ. Press.
Mangel, M. and Clark, C. W. 1988. Dynamic modeling in behavioral ecology. – Princeton Univ. Press.
Mangel, M. and Stamps, J. 2001. Tradeoffs between growth and mortality and the maintenance of individual variation in growth. – Evol. Ecol. Res. 3: 583–593.
Marchant, T. A. and Peter, R. E. 1986. Seasonal variations in body growth rates and circulating levels of growth hormone in the goldfish, *Carassius auratus*. – J. Exp. Zool. 237: 231–239.
McNamara, J. M. and Houston, A. I. 2009. Integrating function and mechanism. – Trends Ecol. Evol. 24: 670–675.
Mommsen, T. P. 2001. Paradigms of growth in fish. – 4th Int. Symp. Fish Endocrinol. 129: 207–219.
Nelson, R. J. 2000. An introduction to behavioral endocrinology. – Sinauer Associates.
Pörtner, H. O. 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. – J. Exp. Biol. 213: 881–893.
Power, D. M. et al. 2001. Thyroid hormones in growth and development of fish. – Comp. Biochem. Physiol. Part C Toxicol. Pharmacol. 130: 447–459.
Priede, I. G. 1985. Metabolic scope in fishes. – In: Tytler, P. and Calow, P. (eds), Fish energetics: new perspectives. Springer, pp. 33–64.
Pyke, G. H. et al. 1977. Optimal foraging: a selective review of theory and tests. – Q. Rev. Biol. 52: 137–154.
Ricklefs, R. E. and Wikelski, M. 2002. The physiology/life-history nexus. – Trends Ecol. Evol. 17: 462–468.
Ripa, J. and Lundberg, P. 1996. Noise colour and the risk of population extinctions. – Proc. Biol. Sci. 263: 1751–1753.
Robson, H. et al. 2002. Interactions between GH, IGF-I, glucocorticoids and thyroid hormones during skeletal growth. – Pediatr. Res. 52: 137–147.
Rodgers, R. J. et al. 2002. Orexins and appetite regulation. – Neuropeptides 36: 303–325.
Rønnestad, I. et al. 2017. Appetite-controlling endocrine systems in teleosts. – Front. Endocrinol. 8: 73.
Stearns, S. C. 1989. Tradeoffs in life-history evolution. – Funct. Ecol. 3: 259–268.
Stefansson, S. O. et al. 2008. Smoltification. – In: Finn, R. N. and Kapo, B. K. (eds), Fish larval physiology. Science Publishers, Enfield, NH, USA, pp. 639–681.
Stephens, D. W. 1981. The logic of risk-sensitive foraging preferences. – Anim. Behav. 29: 628–629.
Sundström, L. F. et al. 2004. Growth hormone transgenic salmon pay for growth potential with increased predation mortality. – Proc. R. Soc. B 271: S350.
Tinbergen, N. 1963. On aims and methods of ethology. – Z. Tierpsychol. 20: 410–433.
Volkoff, H. et al. 2005. Neuropeptides and the control of food intake in fish. – Gen. Comp. Endocrinol. 142: 3–19.
Volkoff, H. et al. 2017. Appetite regulating factors in pacu (*Piaractus mesopotamicus*): tissue distribution and effects of food quantity and quality on gene expression. – Comp. Biochem. Physiol. A Mol. Integr. Physiol. 203: 241–254.
Weidner, J. et al. 2020. Hormones as adaptive control systems in juvenile fish. – Biol. Open 9: bio046144.
Werner, E. E. and Gilliam, J. F. 1984. The ontogenetic niche and species interactions in size-structured populations. – Annu. Rev. Ecol. Syst. 15: 393–425.
White, B. A. and Henderson, N. E. 1977. Annual variations in the circulating levels of thyroid hormones in the brook trout, *Salvelinus fontinalis*, as measured by radioimmunoassay. – Can. J. Zool. 55: 475–481.
Wilson, P. N. and Osbourn, D. F. 1960. Compensatory growth after undernutrition in mammals and birds. – Biol. Rev. 35: 324–361.
Wingfield, J. C. and Kitaysky, A. S. 2002. Endocrine responses to unpredictable environmental events: stress or anti-stress hormones? – Integr. Comp. Biol. 42: 600–609.
Yan, A.-F. et al. 2016. Goldfish leptin-AI and leptin-AII: function and central mechanism in feeding control. – Int. J. Mol. Sci. 17: 783.
Zera, A. J. and Harshman, L. G. 2001. The physiology of life history trade-offs in animals. – Annu. Rev. Ecol. Syst. 32: 95–126.
Zera, A. J. et al. 2007. Evolutionary endocrinology: the developing synthesis between endocrinology and evolutionary genetics. – Annu. Rev. Ecol. Evol. Syst. 38: 793–817.