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The shaping of senescence in the wild

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A central prediction of classical theories of senescence states that environments posing a high risk of mortality favor the evolution of rapid intrinsic deterioration, or ageing. Although widely cited as being largely corroborated by existing data, empirical support for this prediction has been mixed. Recent theory suggests that this expectation should only be realized under particular circumstances, and this could account for the equivocal empirical findings. Here, we highlight the salient features of some of the recent developments in this field and suggest some ways in which progress might be made. We argue that it is necessary to move beyond the simplistic classical expectation and to take a more comprehensive and precise approach to studies of senescence, both theoretically and empirically.

Introduction

The progressive deterioration in the physiological state of an organism over time, variously termed senescence or ageing [1,2], continues to fascinate present-day researchers as much as it did those who pioneered its investigation. Early interest in the subject [1] was due primarily to the enigma that it posed: given that ageing is accompanied by reductions in fecundity and survival, why has selection not eliminated it? This question was subsequently taken up by such luminaries as Fisher [3], Haldane [4], Medawar [5], Williams [6] and Hamilton [7], who laid the theoretical foundations of the modern evolutionary theory of ageing (Box 1; but see [8]).

It was Medawar [5] who provided the key insight that, even in the absence of ageing, potential contributions to fitness by individuals of a given age must be weighted by the probability of surviving up to that point owing to the constant risk of mortality posed by disease, predation and accidents. Thus, the later in life a trait is first expressed the less visible it will be to selection, because any organism bearing such a trait is increasingly likely to have already succumbed to some environmental hazard. Ageing can then proceed via two non-mutually exclusive mechanisms: mutation accumulation [5] and antagonistic pleiotropy [6].

Mutation accumulation is a process in which deleterious alleles with age-specific effects reach non-zero equilibrium frequencies determined by mutation–selection balance. Owing to the waning force of selection, these equilibrium frequencies tend to increase with age. The adaptive theory of antagonistic pleiotropy uses the notion of life-history tradeoffs [2], where improvements early in life are purchased at a cost to later-age fitness components. In either case, a pattern of progressive deterioration of state with age results [9]. These largely verbal models were later formalized into a quantitative theory by Hamilton [7] and subsequently refined by Charlesworth [9] (Box 1).

Evolutionary predictions of ageing

Irrespective of the relative contributions of these mechanisms, Medawar's insight provides the basis for the fundamental prediction, here termed Williams' hypothesis [6], which asserts that ageing should proceed most rapidly in populations that typically experience the highest rates of environmentally imposed mortality [1,5,6,9–11]. Williams' hypothesis has provided a simple and intuitive prediction for a rapidly growing body of empirical work aimed at assessing the validity of classical theories of ageing. Moreover, as no other environmental factor has been proposed to account for the observed variation in rates of ageing both between and among species, Williams' hypothesis stands as the main predictive tool used by comparative biologists when investigating how senescence schedules are shaped in the wild [9,11–13].

The centrality of this prediction is evidenced by the fact that most recent studies [14–20], review articles [13,21–23] and books [24–26] on the subject cite Williams' hypothesis as a direct corollary of evolutionary theories of senescence that has been largely vindicated by empirical evidence. Nevertheless, its generality has long been questioned on both empirical and theoretical grounds. In *Longevity, Senescence and the Genome* [10], Caleb Finch weighed in with '...the outcome of this prediction is a major issue, and conclusions are by no means straightforward or settled, in my view.' Utilizing the formalism of Hamilton, Abrams [27] has shown that evolutionary predictions can be considerably altered when the effects of density dependence are taken into account. More recent theoretical [28] and empirical [17,29,30] findings offer still further indications that the prevailing wisdom, as expressed in the various statements of Williams' hypothesis, is incomplete.

Williams' hypothesis revisited

Williams' hypothesis is predicated on the premise that the expected future contribution of an organism to total fitness, at any given age, diminishes as the risk of mortality increases, because the probability of surviving to that age is reduced [5,6]. In Williams' original parlance '...low adult death rates should be associated with low rates of senescence, and high adult death rates with high rates of senescence.'[6]. The death rates referred to in this statement result from environmental hazards that act on all adult age classes, senescent or otherwise. This implies that it is the 'extrinsic', or age- and condition-independent, component of environmental hazards that promotes accelerated

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Box 1. Quantifying the costs of senescence

Quantitative models of the verbal theories of Medawar [5] and Williams [6] typically appeal to the formalism introduced by Hamilton [7], who derived expressions governing the effects of changes in age-specific mortality and fecundity on fitness. Fitness is usually measured as the intrinsic rate of increase, r, given implicitly by the solution to the Euler–Lotka equation (E–L) $\sum_{j=0}^{\infty} e^{-rj} l_j m_j = 1$; or, when population size is stable, by the net reproduction rate, $R = \sum_{j=0}^{\infty} l_j m_j$. Here, m_j is fecundity at age j, and l_j the probability of surviving from birth to age j, which can be represented as the product of period survival probabilities up to age j, $\prod_{k=0}^{j-1} p_k$.

Following Hamilton, the fitness effect of a mutation in some trait, z, that affects period survival probability in the interval $x-1$ to x, and/or age-specific fecundity at age y, can be determined from the E–L as Equation Ia and Ib.

$$\frac{dr}{dz} = \begin{cases} \frac{1}{T}\left[\frac{d(\ln p_x)}{dz}\right]\left(\sum_{j=x+1}^{\infty} e^{-rj} l_j m_j\right) \\ \qquad \text{and/or} \\ \frac{1}{T}\left[\frac{dm_y}{dz}\right](e^{-ry} l_y) \end{cases} \qquad \text{[Eqn Ia,Ib]}$$

where $T = \sum_{j=0}^{\infty} j e^{-rj} l_j m_j$ measures generation time.

Hamilton also derived an indicator of the sensitivity of fitness to a senescent change in age-specific survival probability, defined as a change that is first experienced at age x but continues to be felt for all ages thereafter. This is likely to be a more relevant measure of fitness sensitivity for discussions of ageing [27,62], because it reflects the fact that the physiological change that produced the initial decrease in survival is degenerative, and so remains in a state of disrepair. This sensitivity is given by Equation II:

$$\frac{1}{T}\sum_{k=x}^{\infty}\left[\frac{d(\ln p_k)}{dz}\right]\left(\sum_{j=k+1}^{\infty} e^{-rj} l_j m_j\right). \qquad \text{[Eqn II]}$$

The key implication of these expressions is that mutational effects of fixed magnitude [i.e. constant terms in the () parentheses of Eqn I and II], have a diminishing impact on fitness as the age of its expression increases, because the terms in the [] parentheses are decreasing functions of time. This quantifies the arguments of Medawar [5] and Williams [6] regarding the evolutionary origins of ageing.

An important distinction between Equations Ia and II lies in their respective predictions regarding the onset of senescence. Equation Ia is constant before the age-of-maturity and declines monotonically thereafter, implying that senescence begins once reproductive maturity is reached [9]. By contrast, Equation II also declines throughout the pre-reproductive period, so that the force of selection against senescence deterioration begins to wane at birth [62].

Of course, if mutational effects can vary with respect to age, these sensitivities need not decline monotonically. For example, if mutations act on period survival or the natural log of fecundity, the mutational effects in Equation I become $1/p_x$ and m_y, respectively; the fitness sensitivities in Equation I can then, under some conditions, increase over some age ranges [8]. If a mutation causes a senescent change that affects all subsequent age classes identically, then the sensitivity in Equation II cannot be an increasing function of age. Mutational effects that might result in increasing sensitivity over some interval have yet to be explored.

ageing [6,27]. Although 'extrinsic' is often used to refer to any mortality factor with an environmental origin [21,29,31,32] (e.g. predation, parasitism and inclement weather), these same hazards are often likely to depend on the condition or state of an individual.

The term 'rate of ageing' also requires some qualification. Ultimately, this is the rate at which expected contributions to fitness decline with age [11,12], and so is a function of both age-specific mortality and fecundity terms. Williams' hypothesis is therefore most correctly phrased in terms of measures that integrate both these vital rate schedules, such as residual reproductive value [11,31]. In fact, the declining force of selection is expected to affect all traits correlated with fitness, with senescence manifesting as pervasive physiological deterioration [6,12]. In principle, then, a rate of ageing can be extracted from measurements of declining performance, or physiological senescence, in a variety of traits.

Nevertheless, most studies focus on divining rate measures from age-specific mortality data (Box 2). Indeed, many authors cite an increasing mortality rate with age, termed 'actuarial senescence', as the defining characteristic of

Box 2. Mortality models and rates of ageing

Following the work of Finch *et al.* [10], several studies have attempted to construct measures of the rate of ageing with parameters obtained from fitting various models to age-specific mortality data. The Gompertz [10,29,33,56,63,64] and Weibull [43,52] models have been particularly used in this regard.

Gompertz functions represent total age-specific mortality at any age x, m_x, as the product of an initial mortality rate experienced by young adults, m_0, and an exponential component owing to senescent deterioration, $e^{\gamma x}$. Both the Gompertz ageing parameter [10,32,33,56], γ, (or, equivalently, the mortality rate doubling time, $\ln 2/\gamma$) and the quantity $\omega_G = \sqrt{m_0 \gamma}$ [29,52,55] have been used as indicators of the rate of ageing. The difference between these two rates highlights a point of contention in the gerontological literature. Some authors argue that changes in m_0 represent acute alterations to age-specific mortality and thus do not affect the rate of ageing [34]. Others have noted that the increase in mortality owing to senescence, $m_x - m_0$, is a function of m_0, implying that this parameter influences the cost of senescence and should therefore be included in a measure of ageing rate [27,55].

The Weibull model partitions total age-specific mortality into a sum of initial mortality and a term owing to senescent deterioration, so that $m_x = m_0 + \alpha x^{\beta}$. In this case, the increase in mortality owing to ageing, αx^{β}, is independent of m_0, and the parameter $\omega_W = \alpha^{1/(1+\beta)}$ has been used to quantify the rate of ageing [43,52,55].

A general criticism of these rate measures is that, contrary to some claims [55], they are derived from models that are entirely descriptive conveniences. As such, the parameters obtained from them have no intrinsic biological meaning [61]. There is also little indication that either function can be derived from underlying evolutionary principles [10,27,62]. A model of the mutation accumulation mechanism by Charlesworth [65] does obtain an expression for age-specific mortality that has Gompertz-like form, but the generality of this result has recently been questioned [66]. Antagonistic pleiotropy models have also been used to generate Gompertz mortality curves, but only under very specific assumptions [67].

Many studies [63] have described how various interventions influence the different parameters of fitted mortality models and, by extension, whether they influence the rate of ageing. A sounder course of action is to determine if and how a particular treatment influences the fitness costs of ageing, rather than on whether it alters some *a priori* notion of rate change.

ageing [1,19,33–35]. Actuarial senescence can presumably be effected either through deteriorative changes that cause death regardless of the environment of the organisms, or by enhancing susceptibility to environmental hazards. In the former case, such mortality has been termed 'intrinsic' [15].

However, entirely mortality-based definitions of senescence can be misleading. For example, recent theory questioning the general validity of Hamilton's finding that 'senescence is expected to be an inevitable consequence of the working of natural selection' [7] has considered the possibility of negative senescence, defined as a decreasing mortality rate with age [35]. However, factors such as growth and learning might reduce exposure to hazards such predation as an organism ages. If this reduction is greater than any increase in mortality caused by senescent deterioration, then a decline in age-specific mortality rates over some age intervals would be observed. Moreover, given tradeoffs between organismal state early and late in life, life-history optimization [6,12] can result in early life improvements that potentially including decreasing mortality rates [11,12]. In either of these cases, decreasing age-specific mortality rates can occur despite a continual weakening of the force of natural selection against senescent deterioration, which is predicted by Hamilton's work (Box 1).

Empirical evidence

Experimental evolution studies are one way in which Williams' hypothesis has been tested. Adopting the intrinsic–extrinsic terminology, Stearns *et al.* [15] found support for the hypothesis that a higher extrinsic mortality rate should favor the evolution of higher intrinsic mortality rates [1,15,19,36] using laboratory populations of *Drosophila melanogaster*.

Evidence from broad, cross-species contrasts have provided, at best, weak support. Using mortality data from natural populations of mammals, Promislow [33] found no relationship between an index of the rate of actuarial senescence (Box 2) and an estimate of the mortality rate experience by young adults. Other works have relied on maximum lifespan as an indicator of the rate of ageing, although differences in extrinsic mortality are only inferred from differences in habitat, lifestyle or ecology that limit predation risks. Eusociality [18,37], and toxin production [20] have been interpreted in this light.

Longer maximum lifespans of birds and bats relative to similarly sized flightless birds and mammals [6,9,38,39] is the piece of comparative evidence most commonly cited as confirming Williams' hypothesis. Finch [10], however, points out that some bat species, despite high mortality rates as young adults, nevertheless seem to exhibit very slow senescence. Carey and Gruenfelder [40] suggest that avian longevities have been shaped by social structure, wherein selection on old individuals remains strong owing to potential inclusive fitness contributions obtained by providing care or resources to relatives. This intriguing idea has recently been formalized with a theory of intergenerational transfers [41]. Another possibility is that flight exposes its bearers to more conditionally hazardous environments, such that even slightly degenerative physiological changes might greatly reduce survival probabilities [10]. This idea has also received some theoretical consideration [28].

Data from comparisons of closely related species are similarly equivocal, with some results apparently conforming to standard predictions [16,19,36,42,43], and others not [14,17,29,30]. Of course, there are many possible reasons for this overall lack of accord. Theory [27,28] has focused on the role that environmental context can have in altering patterns of selection imposed by environmental hazards. Environment can also materially alter the expression of senescence [10], and so influence the way that ageing patterns are compared. Finally, all these studies quantify and compare rates of ageing in different ways, and this too might be a crucial factor.

Environmental effects: selection

Stearns *et al.*'s [15] study provides the best empirical support for Williams' hypothesis, although it is unclear how their results might apply to natural populations, where total mortality might not partition so cleanly into intrinsic and extrinsic components. In their experimental scheme [15], population densities were maintained at constant sizes, while mortality was imposed in an age- and condition-independent fashion, hence 'extrinsic' in the exact sense. How do such demographic and hazard effects influence selection on senescence?

Density dependence

When age-specific fecundity and mortality rates depend on population density, a change in extrinsic mortality can indirectly influence selection pressures shaping senescence schedules via feedback through its effects on these vital rates, which change plastically to re-establish a stationary population size [27]. For example, a high extrinsic mortality rate might reduce population density, resulting in each surviving individual obtaining a greater share of resources and, thus, enjoying increased survival and/or fecundity at some ages. Some simple patterns of change in vital rates either enhance or diminish the sensitivity of fitness to senescent deterioration at all ages, enabling unambiguous predictions of either increased or decreased senescence (Table 1). When density effects produce more complex patterns of change, it becomes difficult to draw any general conclusions about the way in which senescence should evolve. Density dependence in vital rates is a well-establish phenomenon [44], implying that such effects might be important determinants of the selection pressures acting on senescence schedules in natural populations.

Condition–environment interactions

Abrams [27] modeled the evolution of intrinsic mortality in response to changes in extrinsic mortality, but noted that results might be similarly diverse if one instead considered physiological senescence in response to changes in age- and condition-dependent hazards. The crucial issue is whether senescence of the physiological trait in question increases susceptibility to the hazard. If so, then increased environmental hazard can strengthen the force of selection against senescent deterioration, sometimes leading to the prediction that high environmental hazards select for decreased deterioration [28] (Table 1).

Table 1. Expected response of rate of senescence to increases in mortality under various forms of density-dependent population regulation[a]

Population dynamics / Mortality risk	Density independent	Density affects survival equally at all ages	Density affects fertility equally at all ages or juvenile survival	Density affects survival or fertility in late-life	Density affects fertility at all ages and late-life survival
Condition independent [27] (i.e. 'extrinsic')	No response	No response	More rapid	Less rapid	Less rapid at early and late ages; more rapid at intermediate ages
Condition dependent [28]	Less rapid at early ages, more rapid at late ages[b]	Diversity of outcomes possible	Diversity of outcomes possible	Diversity of outcomes possible	Diversity of outcomes possible

[a]Boxes give the predicted response assuming mortality type (rows) and type of density dependence (columns).
[b]A possible outcome, rather than a general prediction.

Whereas age-related enhanced susceptibility to hazards such as disease is well documented in the medical literature, empirical studies of such interactions in wild populations are surprisingly rare. Senescence in immune function is an important candidate for an interactive source of deterioration, and has been investigated in two bumblebee species, *Bombus terrestris* and *B. lucorum*, where it was found that the ability to melanize a foreign body declined with age [45]. Although this was a laboratory study, declines began before the age of mean life expectancy in the wild and, hence, might be relevant in a natural setting.

Increased susceptibility of senescent age classes to predation has been observed in ungulates [46–50] and salmon [30,51]. In a similar vein, Ricklefs and Scheuerlein [52] compared a derived measure of the rate of actuarial senescence between wild and captive mammals and concluded that ageing, in grassland predator and prey species, entailed an increasing susceptibility to environmental hazards. By contrast, age-specific increases in mortality were found to result from catastrophic intrinsic deterioration in the other species examined, in agreement with an earlier study of birds [53].

Environmental effects: expression

It is often the case that senescence schedules are assayed in controlled environments [14,16,17,29,42]. This can be misleading as, in addition to modulating selection on ageing schedules, factors present in the natural environment of the organism can also directly alter the expression of senescence [10]. For example, a recent study of Norwegian red deer *Cervus elaphus* [54] found that the age-of-onset and the rate of physiological senescence were functions of population density, although apparently only in males.

A similar issue arises for natural hazards, and a possible illustration of this is provided by contrasting the results of two recent tests of Williams' hypothesis [19,29]. In the first [19], patterns of actuarial senescence were quantified from field-collected data for two distinct Trinidadian guppy *Poecilia reticulata* populations. Although both populations inhabited streams with low predation pressures, one was descended from a population that was translocated from a high predation stream in 1981. Females from the population that had been derived from the high predation stream experienced an earlier onset and more rapid rate of senescence, and this was interpreted as conforming to the classical prediction.

In a second test [29], actuarial senescence was assayed, in the absence of predators, in laboratory-reared populations of guppies from high and low predation sites. In this case, the opposite result was obtained: guppies derived from the high predation population exhibited a slower rate of ageing relative to the low predation guppies. Additionally, physiological senescence was quantified by assaying age-specific declines in the so-called 'fast start response', an indicator of predator evasion ability. In contrast to the actuarial results, guppies from the high predation environment deteriorated more rapidly with age in this physiological measure.

A consequence of these patterns of physiological deterioration is that age-specific mortality rates of guppies from the high predation regime would probably be more sensitive to changes in predation level than those of low predation guppies. Indeed, it would not be surprising if the rate of deterioration in survival more closely paralleled that of physiology if it had been measured in the presence of predators.

The shape of senescence: quantifying the rate of ageing

The second of the above studies enables some insights into another fundamental issue that must be addressed when testing Williams' hypothesis: how to quantify the rate of ageing. To simplify comparisons between populations, several unitary indices have been proposed (Box 2). Reznick *et al.* [29] utilize one such index (proposed in [52,55]) to conclude that guppies derived from high predation sites experience less rapid actuarial senescence than do low predation ones. However, a reanalysis [29] using a different index (proposed in [10,56]) reversed this prediction. A third index indicated that rates of ageing were not significantly different between the two populations. This lack of agreement is problematic, as all of these indices have been used to provide evidence for or against Williams' hypothesis.

The root of this discrepancy probably lies in the fact that unitary descriptors are too coarse to characterize accurately the often complex age-specific pattern of ageing rates. From an empirical perspective, considerable variation across age classes in mortality rate accelerations has been demonstrated in data from beetles [34], medflys [57] and humans [58]. We might also expect this on theoretical grounds: if density dependence and interactions between senescent deterioration and environmental hazards are operating, selection might act to reduce senescent deterioration at some ages, and increase it at others, in response to increased environmental hazards [27,28]. When integrated over an entire lifespan into a single index of ageing, these local effects are obscured, and much of the information regarding how senescence is shaped by the external hazard can be lost.

Conclusions and future directions

Despite common sentiment to the contrary, the present weight of evidence has failed to establish Williams' hypothesis as a general prediction of the way that environmental

Box 3. Senescence from a life-history perspective

Life history can be pictured as a set of resources flowing from a common pool into a series of metric traits that are correlated with the components of fitness [68]. This is an appropriate context in which to discuss ageing, as senescent declines in fitness components are commonly viewed as resulting from a lack of investment in some underlying 'maintenance' trait [67,69]. Imagine, for example, that T_2 is a key somatic maintenance trait. Investment in this trait increases late-life survivorship and fecundity, whereas T_1 and T_3 are traits that increase early-life survivorship and fecundity, respectively. Under William's original conjecture, high environmental hazard can favor resource allocation to T_1 and T_3 at the expense of T_2.

This framework also informs the relationship between underlying physiological traits and senescent decreases in fitness. For example, previous work on Trinidadian guppy populations [29] has indicated that predation is a major environmental hazard, so that escape mechanisms are likely to be important determinants of mortality. By defining T_1 as swimming performance, its effect of survivorship therefore depends upon the predation environment, represented by 'E' in Figure I (i.e. there is an interaction). Specifically, swimming performance has a greater effect on survivorship when predation rates are high. Thus, one would expect selection for increased swimming performance in high predation environments. This would be seen as higher swimming performance in guppies evolved under high predation regimes, as found by Reznick *et al.* [29].

Interestingly, had we chosen a different underlying trait to measure, say T_3, we could not predict the effect of predation regime on its expression. This is true for any possible function of T_3, the reason being that increased investment in T_1 will result in decreased investment in some number of other traits, including perhaps T_3. This tradeoff might mask selection for increased expression of T_3 under the high predation regime. Choosing the informative trait rests on knowledge of the details of the selective regime and the natural history of the organism [61]. In the case of the guppies, the selective regime was predation by larger fish, and the key physiological trait was the ability of the guppy to escape predation.

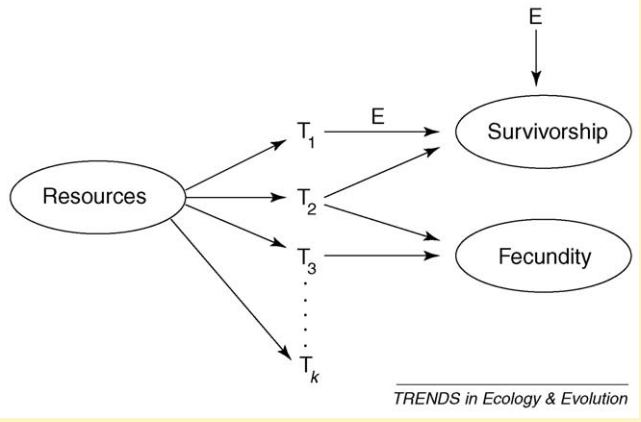

Figure I.

hazards shape ageing schedules in the wild. It must be the case that the overall inconclusive findings of the existing body of empirical work can be attributed, in part, to a paucity of relevant studies. Here, we have suggested that some of this discord might also be due to conceptual and methodological issues regarding the definition and measurement of some fundamental concepts and quantities.

It has previously been argued [11] that accurate tests of Williams' hypothesis require population comparisons to occur in environments that closely mimic natural conditions, minus the hazard assumed to have imposed selection, because many life-history traits exhibit considerable environmental plasticity. However, the existence of such plasticity is precisely why it can be crucial to include these hazards: in their absence, the expression of senescence in terms of mortality, fecundity [27] or even other physiological measures [54], might be considerably altered. From the perspective of comparing rates of ageing between populations that differ in their historical exposure to some hazard, this entails using fully factorial experimental designs, including the hazard level of both environments. Such designs will provide the most complete picture of how the different levels of hazard have affected evolution, as well as how physiological state interacts with the environment to generate fitness effects.

One potential obstacle in such designs is that comparisons will be rendered impossible when one or both of the study populations typically experience extrinsic mortality rates that are high enough to preclude survival to ages at which senescence becomes detectable. Indeed, common wisdom holds that senescence should be largely unobservable in the wild for this reason [21,59]. Although this is undoubtedly true in some cases [19], a particularly compelling counterexample is provided by the recent demonstration of actuarial and reproductive senescence in a natural population of the antler fly *Protopiophila litigate* [60], which suffers a daily extrinsic mortality rate of ~13%. Although it remains to be seen how broadly this empirical prescription can be implemented, studies such as this offer hope that it should be achievable in many systems.

In situations where fully factorial experiments are deemed impossible, some insights can still be gained by making measurements of age-specific performance in physiological traits that are less plastic with respect to environmental hazards. The traits to focus on should be ones whose deterioration is most likely to elevate mortality and/or decrease fecundity in a natural setting [29,61]. Determining these will often require a detailed knowledge of the natural history of the species of interest (Box 3).

In either case, it will no longer be tenable to characterize patterns of senescence as being either faster or slower. Rather, it must be acknowledged that ageing schedules are functions, which can differ in many ways that are not adequately captured by single-parameter summary measures. We are now at a point, both in terms of the level of sophistication of empirical studies and the development of theory, where we have the opportunity to investigate more precisely the connection between the extent and quality of externally imposed mortality and its effects on the evolution of ageing. By this route, we can move beyond classical statements of Williams' hypothesis and begin to develop a more comprehensive understanding of the ways that environmental hazards shape senescence schedules in nature.

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References

1 Rose, M.R. (1991) *Evolutionary Biology of Aging,* Oxford University Press
2 Roff, D. (2002) *Life History Evolution,* Sinauer Associates
3 Fisher, R.A. (1930) *The Genetical Theory of Natural Selection,* Clarendon Press
4 Haldane, J.B.S. (1941) *New Paths in Genetics,* Allen & Unwin
5 Medawar, P.B. (1952) *An Unsolved Problem in Biology,* H.K. Lewis
6 Williams, G.C. (1957) Pleiotropy, natural selection, and the evolution of senescence. *Evolution* 11, 398–411

7 Hamilton, W.D. (1966) The moulding of senescence by natural selection. *J. Theor. Biol.* 12, 12–45
8 Baudisch, A. (2005) Hamilton's indicators of the force of selection. *Proc. Natl. Acad. Sci. U. S. A.* 23, 8263–8268
9 Charlesworth, B. (1994) *Evolution in Age-Structured Populations,* 2nd ednCambridge University Press
10 Finch, C.E. (1990) *Longevity, Senescence, and the Genome,* University of Chicago Press
11 Partridge, L. and Barton, N.H. (1996) On measuring the rate of ageing. *Proc. R. Soc. B* 263, 1365–1371
12 Partridge, L. (1997) Evolutionary biology and age-related mortality, In *Between Zeus and the Salmon: The Biodemography of Longevity* (Wachter, K.W. and Finch, C.E., eds), pp. 78–95, National Academy Press
13 Hughes, K.A. and Reynolds, R.M. (2005) Evolutionary and mechanistic theories of aging. *Annu. Rev. Entomol.* 50, 421–445
14 Gray, D.A. and Cade, W.H. (2000) Senescence in field crickets (Orthoptera; Gryllidae): examining the effects of sex and a sex-biased parasitoid. *Can. J. Zool.* 78, 140–143
15 Stearns, S.C. *et al.* (2000) Experimental evolution of aging, growth, and reproduction in fruitflies. *Proc. Natl. Acad. Sci. U. S. A.* 97, 3309–3313
16 Dudycha, J.L. (2001) The senescence of daphnia from risky and safe habitats. *Ecol. Lett.* 4, 102–105
17 Miller, R.A. *et al.* (2002) Longer life spans and delayed maturation in wild-derived mice. *Exp. Biol. Med.* 227, 500–508
18 Sherman, P.W. and Jarvis, J.U.M. (2002) Extraordinary life spans of naked mole-rats (*Heterocephalus glaber*). *J. Zool.* 258, 307–311
19 Bryant, M.J. and Reznick, D. (2004) Comparative studies of senescence in natural populations of guppies. *Am. Nat.* 163, 55–68
20 Blanco, M.A. and Sherman, P.W. (2005) Maximum longevities of chemically protected and non-protected fishes, reptiles, and amphibians support evolutionary hypotheses of aging. *Mech. Age. Dev.* 126, 794–803
21 Kirkwood, T.B.L. and Austad, S.N. (2000) Why do we age? *Nature* 408, 233–238
22 Partridge, L. and Gems, D. (2000) The evolution of longevity. *Curr. Biol.* 12, 544–546
23 Weinert, B.T. and Timiras, P.S. (2003) Theories of aging. *J. Appl. Physiol.* 95, 1706–1716
24 Austad, S.N. (1997) *Why We Age: What Science Is Discovering About the Body's Journey Through Life,* John Wiley & Sons
25 Wachter, K.W. (1997) Between Zeus and the salmon: introduction, In *Between Zeus and the Salmon: The Biodemography of Longevity* (Wachter, K.W. and Finch, C.E., eds), pp. 1–16, National Academy Press
26 Clark, W.R. (1999) *A Means to an End: The Biological Basis of Aging and Death,* Oxford University Press
27 Abrams, P.A. (1993) Does increased mortality favor the evolution of more rapid senescence. *Evolution* 47, 877–887
28 Williams, P.D. and Day, T. (2003) Antagonistic pleiotropy, mortality source interactions, and the evolutionary theory of senescence. *Evolution* 57, 1478–1488
29 Reznick, D.N. *et al.* (2004) Effect of extrinsic mortality on the evolution of senescence in guppies. *Nature* 431, 1095–1099
30 Morbey, Y.E. *et al.* (2005) Rapid senescence in pacific salmon. *Am. Nat.* 166, 556–568
31 Partridge, L. (2001) Evolutionary theories of ageing applied to long-lived organisms. *Exp. Gerontol.* 36, 641–650
32 Bronikowski, A.M. and Promislow, D.L. (2005) Testing evolutionary theories of aging in wild populations. *Trends Ecol. Evol.* 20, 271–273
33 Promislow, D.L. (1991) Senescence in natural populations of mammals: a comparative study. *Evolution* 45, 1869–1887
34 Tatar, M. *et al.* (1993) Long-term cost of reproduction with and without accelerated senescence in *Callosobruchus maculates*: analysis of age-specific mortality. *Evolution* 47, 1302–1312
35 Vaupel, J.W. *et al.* (2004) The case for negative senescence. *Theor. Pop. Biol.* 65, 339–351
36 Austad, S.N. (1993) Retarded senescence in an insular population of Virginia opossums (*Didelphis virginia*). *J. Zool.* 229, 695–708
37 Keller, L. and Genoud, M. (1997) Extraordinary lifespans in ants: a test of evolutionary theories of ageing. *Nature* 389, 958–960
38 Austad, S.N. and Fischer, K.E. (1991) Mammalian aging, metabolism, and ecology: evidence from the bats and marsupials. *J. Gerontol. B* 46, 47–53
39 Holmes, D.J. and Austad, S.N. (1995) The evolution of avian senescence patterns: implications for understanding primary aging processes. *Am. Zool.* 35, 307–317
40 Carey, J.R. and Gruenfelder, C. (1997) Population biology of the elderly, In *Between Zeus and the Salmon: The Biodemography of Longevity* (Wachter, K.W. and Finch, C.E., eds), pp. 127–160, National Academy Press
41 Lee, R.D. (2003) Rethinking the evolutionary theory of aging: transfers, not births, shape senescence in social species. *Proc. Natl. Acad. Sci. U. S. A.* 100, 9637–9642
42 Tatar, M. *et al.* (1997) Altitudinal variation for senescence in *Melanoplus* grasshoppers. *Oecologia* 111, 357–364
43 Ricklefs, R.E. (1998) Evolutionary theories of aging: confirmation of a fundamental prediction, with implications for the genetic basis and evolution of life span. *Am. Nat.* 152, 24–44
44 Caughley, G. (1977) *Analysis of Vertebrate Populations,* Wiley-Interscience
45 Doums, C. *et al.* (2002) Senescence of immune defence in *Bombus* workers. *Ecol. Entomol.* 27, 138–144
46 Fuller, T.K. and Keith, L.B. (1980) Wolf population dynamics and prey relationships in northeastern Alberta. *J. Wild. Manag.* 44, 583–602
47 Bjorge, R.R. and Gunson, J.R. (1989) Wolf, *Canis lupus*, population characteristics and prey relationships near Simonette River, Alberta. *Can. Field-Nat.* 103, 327–334
48 Boyd, D.K. *et al.* (1994) Prey taken by colonizing wolves and hunters in the Glacier National Park area. *J. Wild. Manag.* 58, 289–295
49 Mech, L.D. *et al.* (1995) Patterns of prey selection by wolves in Denali National Park, Alaska, In *Ecology and Conservation of Wolves in a Changing World* (Carbyn, L.D. et al. eds), pp. 231–243, Canadian Circumpolar Institute
50 Smith, D.W. *et al.* (2004) Winter prey selection and estimation of wolf kill rates in Yellowstone national park, 1995–2000. *J. Wild. Manag.* 68, 153–166
51 Gende, S.M. *et al.* (2004) Brown bears selectively kill salmon with higher energy content but only in habitats that facilitate choice. *Oikos* 104, 518–528
52 Ricklefs, R.E. and Scheuerlein, A. (2001) Comparison of aging-related mortality among birds and mammals. *Exp. Gerontol.* 36, 845–857
53 Ricklefs, R.E. (2000) Intrinsic aging-related mortality in birds. *J. Avian. Biol.* 31, 103–111
54 Mysterud, A. *et al.* (2001) Effects of age, sex and density on body weight of Norwegian red deer: evidence of density-dependent senescence. *Proc. R. Soc. B* 268, 911–919
55 Ricklefs, R.E. and Scheuerlein, A. (2002) Biological implications of the Weibull and Gompertz models of aging. *J. Geronotol. A* 57, B69–B76
56 Finch, *et al.* (1990) Slow mortality-rate accelerations during aging in some animals approximate that of humans. *Science* 249, 902–905
57 Carey, J.R. and Liedo, P. (1995) Sex-specific life table aging rates in large medfly cohorts. *Exp. Gerontol.* 30, 315–325
58 Horiuchi, S. and Wilmoth, J.R. (1997) Age patterns of the life table aging rate for major causes of death in Japan, 1951–1990. *J. Gerontol.* 52, B67–B77
59 Hayflick, L. (2000) The future of ageing. *Nature* 408, 267–269
60 Bondurianski, R. and Brassil, C.E. (2002) Rapid and costly ageing in wild male flies. *Nature* 420, 377
61 Williams, G.C. (1999) The Tithonus error in modern gerontology. *Q. Rev. Biol.* 74, 405–415
62 Abrams, P. (1991) The fitness costs of senescence: the evolutionary importance of events early in adult life. *Evol. Ecol.* 5, 343–360
63 Pletcher, S.D. *et al.* (2000) Why do life spans differ? Partitioning mean longevity differences in terms of age-specific mortality parameters *J. Gerontol.* 55A, B381–B389
64 Bronikowski, A.M. *et al.* (2002) The aging baboon: comparative demography in a non-human primate. *Proc. Natl. Acad. Sci. U. S. A.* 99, 9591–9595
65 Charlesworth, B. (2001) Patterns of age-specific means and genetic variances of mortality rates predicted by the mutation-accumulation theory of ageing. *J. Theor. Biol.* 210, 47–65
66 Steinsaltz, D. *et al.* (2005) A generalized model of mutation–selection balance with applications to aging. *Adv. Appl. Math.* 35, 16–33
67 Abrams, P.A. and Ludwig, D. (1995) Optimality theory, Gompertz' Law, and the disposable soma theory of senescence. *Evolution* 49, 1055–1066
68 Rowe, L. and Houle, D. (1996) The lek paradox and the capture of genetic variance by condition-dependent traits. *Proc. R. Soc. B* 263, 1415–1421
69 Kirkwood, T.B.L. (2002) Evolution of ageing. *Mech. Age. Dev.* 123, 737–745