



Lifespan divergence between social insect castes: challenges and opportunities for evolutionary theories of aging

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The extraordinarily long lifespans of queens (and kings) in eusocial insects and the strikingly large differences in life expectancy between workers and queens challenge our understanding of the evolution of aging and provide unique opportunities for studying the causes underlying adaptive variation in lifespan within species. Here we review the major evolutionary theories of aging, focusing on their scope and limitations when applied to social insects. We show that reproductive division of labor, interactions between kin, caste-specific gene regulation networks, and the integration of colony-level trade-offs with individual-level trade-offs provide challenges to the classical theories. We briefly indicate how these challenges could be met in future models of adaptive phenotypic plasticity in lifespan between and within different castes.

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Introduction

Lifespan is a highly variable trait across the tree of life that varies up to 5000 fold within the insect clade alone. Variation within species is generally much smaller [1,2], except in social insects, where queens have lifespans of up to 28 years [3], while worker lifespan is typically much shorter and similar to that of their solitary ancestors [4]. Moreover, worker lifespan is often condition dependent and highly plastic in response to extrinsic factors such as temperature and season [5,6], to intrinsic factors such as body size and metabolic rate [5,7], and to colony-level factors such as colony size and task division [8–12]. This

enormous intraspecific variation makes social insects ideal model systems for aging research without the limitations of interspecific comparison that suffers from confounding factors such as genetic architecture, physiology, ecology and so on [4].

Several authors [3,7,13,14] have argued that the differences in lifespan between queens and workers are easily explained by the classical evolutionary theories of aging [15–17], which predict that senescence should be positively related to the level of extrinsic mortality. According to this logic, queens live much longer than workers since they are exposed to much lower extrinsic mortality, which in turn leads to much stronger selection against senescence. However, this argument may be misleading, since the classical theories for the evolution of aging do not directly apply to social insects, for at least four reasons. First, social insect colonies are not only age-structured, as classical theories assume, but also strongly structured along other important state variables such as caste or task. Recent models [18] show that a crucial pillar of the classical framework, the declining force of natural selection with age [19], crumbles under this richer structure. Second, depending on the degree of sociality in social insects [20], fitness mainly reflects colony output, rather than individual reproductive success. As a result, another crucial pillar of classical theory, the individual-level trade-off between current and future reproductive success, must cave in to the weight of trade-offs at the colony level [21•]. Since workers share resources with the queen, her offspring and with each other, some colony members — especially the queen — are essentially liberated from individual-level trade-offs. Third, since workers in highly eusocial societies typically have little or no direct ‘personal’ fitness, unlike the individuals in classical theory, indirect fitness considerations must be incorporated into models that are applicable to social insects. Fourth, unlike in classical models, selection on different individuals is not independent, but due to overlapping regulatory gene networks shared by queen and workers, selection on age-specific fitness will be affected by between-caste pleiotropy.

In the rest of this review we will first discuss how the age-specific force of selection [19], a central concept in classical theory, is affected by the caste-structure of social insects. Next we review the three classical evolutionary

theories of aging — the mutation accumulation, antagonistic pleiotropy and disposable soma models [15–17, Chapter 1 of this issue (Korb and Kuhn)] — and discuss to what extent they apply — or fail to do so — to social insects. Finally, we indicate some future directions for evolutionary modeling of aging in social insects.

The force of selection in age- and state-structured populations

A central organizing concept in all evolutionary theories of aging is that, in an age-structured population, the strength or ‘force’ of natural selection tends to decrease with age. In other words, a mutation with a given phenotypic effect has a higher impact on fitness if its effect materializes early in life than if it is expressed later in life. The logic is that random extrinsic mortality inevitably guarantees a higher abundance — and a correspondingly greater target for natural selection — of younger age classes, thus casting a ‘shadow of selection’ on older age classes. This idea was first formalized mathematically by Hamilton [19] who derived formulas for the force of selection in an age-structured population (see Box 1).

Accordingly, selection on phenotypic traits associated with senescence should be stronger in organisms exposed to lower extrinsic mortality and weaker in organisms facing higher extrinsic mortality, provided extrinsic mortality is not entirely age-independent [22,23]. This, however, does not necessarily explain the difference in lifespan between queens (lower extrinsic mortality) and workers (higher extrinsic mortality), since Hamilton’s argument does not automatically generalize to populations structured according to states other than age (see Box 1) [24**].

A complicating factor is that ‘extrinsic’ mortality is not easy to define for social insects, since mortality differences between castes might reflect ‘intrinsic’ strategic decisions. For example, one might argue that foraging workers have evolved a shorter lifespan in response to extrinsic mortality [7], but it might actually be the other way around: individuals with the lowest life expectancy are assigned the riskiest (in terms of mortality) tasks [10]. Modeling the feedback between the adaptive allocation of extrinsic risks to different parts of the colony and the evolution of caste and state-specific lifespan, presents an important future challenge beyond the scope of current evolutionary theories of aging. Some initial progress has been made in this direction: a recent model shows that decreasing worker lifespan is adaptive for colonies when extrinsic mortality rises, if reduced worker lifespan is positively associated with the per capita rate of resources harvesting by workers [21**].

Classical evolutionary theories of aging and their application to social insects

Hamilton’s force-of-selection principle provides a general framework for fitness comparisons among mutations that

act in an age-specific manner. In line with this principle, three major evolutionary theories of aging have been formulated that differ in their assumptions on the nature of the mutations that contribute to senescence.

Medawar’s (1952) mutation accumulation (MA) theory reflects the idea that, due to the declining force of selection with age, deleterious mutations are more strongly selected against if they reduce viability or fecundity early in life than if their phenotypic effects become visible only later in life [15]. Late-acting mutations can therefore accumulate in the genome and lead to senescence at more advanced ages. A challenge in applying MA theory to social insects is that the divergence in lifespan between queen and workers is difficult to explain in this framework. An increased lifespan of queens might be caused by more efficient purging of deleterious late-acting mutations due to an increase in the age-specific force of selection in queens (see Box 1), and a decreased lifespan of workers could result from an accumulation of late-acting deleterious alleles, but the theory offers no explanation for how both can happen at the same time [21**,25–27]. It is certainly possible that part of the genome only ever gets expressed in workers and never in queens, and vice versa, but it is an open question whether caste-specific regulatory gene networks exist that are decoupled to such an extent.

Although Medawar already noted that selection may favor antagonistic alleles with positive fitness effects early in life and negative effects later in life, Williams’ (1957) is usually credited with the more fully developed antagonistic pleiotropy (AP) theory of aging [16] that was formalized by Charlesworth [28]. Because of the declining force of selection with age, the net fitness effect of a mutation that has a beneficial phenotypic effects in young individuals but deleterious effects in old individuals can be positive [16], even if the deleterious effects are larger. Thus, in combination with Hamilton’s force-of-selection principle the trade-off between early versus late reproduction may pave the way to the evolution of senescence [16,29]. When applied to social insects, the theory suffers from the same problem as the MA theory: it can only work for mutations that occur in genes with caste-limited expression — otherwise it cannot be reconciled with the divergence in lifespan between the castes. This problem partially disappears if antagonistic effects of mutations do not occur within castes, but rather between castes. For example, mutations could be fixed in the genome if they have antagonistic effects on queen and worker lifespan, as long as they have a net positive effect on the fitness of the colony. Alternatively, antagonistic alleles that are triggered by different caste-specific environmental conditions could lead to the evolution and regulation of different aging phenotypes [25].

Kirkwood’s (1977) disposable soma (DS) theory [17] may be viewed as a special mechanistic case of the theory of

Box 1 Hamilton's age-specific force of selection

The classic evolutionary theories of aging are based on the notion that the strength or 'force' of selection declines with age. Intuitively, the logic goes like this: genes that are expressed only in very old individuals are rarely exposed to selection since, especially in the wild, the vast majority of individuals die before reaching a ripe old age. More generally, the probability of exposure to selection at any given age should be proportional to the probability of surviving until that age. Hamilton [19] was the first to formally quantify this notion by deriving mathematical expressions for the sensitivity of the 'Malthusian parameter' r — a standard fitness measure in life history theory — to changes in age-specific survival and fecundity. Here we focus on changes in survival only. Since survival is a multiplicative process, changes in survival are additive on a log-scale (more on this below), and this is why Hamilton modeled effects on fitness of small changes in the logarithm of survival. Before showing Hamilton's main result in his own formalism, we give a new and more intuitive formula based on matrix population models. Let p_{i-1} be the probability of survival from age $i-1$ to age i . Then the sensitivity of r with respect to log-survival can be written as follows:

$$\frac{\partial r}{\partial \log p_{i-1}} = u_i \frac{v_i}{\bar{v}}. \quad (1)$$

Here $u_i = \ell_i e^{-r(i-1)}$ is the relative frequency of age class i , where $\ell_i = p_1 p_2 \dots p_{i-1}$ is the probability of survival from age 1 to age i , $u_1 = 1 / \sum_{i \geq 1} \ell_i e^{-r(i-1)}$ is a normalizing constant, $v_i = \ell_i^{-1} e^{r(i-1)} v_1 \sum_{j \geq i} \ell_j F_j e^{-rj}$ is the reproductive value (RV) of individuals in age class i , where F_j is fecundity at age j , and $\bar{v} = \sum_{i \geq 1} u_i v_i$ is the average RV in the population. Thus, the age-specific force of selection is, indeed, proportional to survival until that age, multiplied by the age-specific RV relative to the average RV in the population. Hamilton's equivalent formula is given by

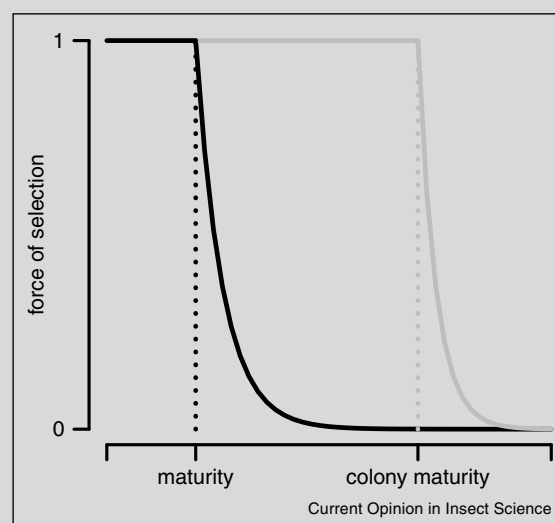
$$\frac{\partial r}{\partial \log p_{i-1}} = \frac{\sum_{j \geq i} \ell_j F_j e^{-rj}}{\sum_{j \geq 1} j \ell_j F_j e^{-rj}} \quad (2)$$

The numerator in this formula is often said to represent the 'remaining' lifetime fertility at age i (e.g. [32,44]), and is not wrong *per se*, but it is more accurate to say that the numerator is proportional to remaining fertility multiplied by the probability to survive until age i , as Eq. (1) more clearly shows. The denominator of Eq. (2) is often interpreted as a measure of generation length, but it is not clear why this interpretation is relevant to aging, while Eq. (1) shows that the denominator is an expression of average fitness with which to compare age-specific fitness. Thus, Eq. (1) is easier to interpret and generalize, but Eq. (2) has the advantage that it is easier to spot that the numerator decreases with age after the age of first breeding and equals unity up to the age of first breeding (the smallest age i where $F_i > 0$) (see Fig. 1).

Hamilton's more or less implicit assumption of mutations acting additively on a logarithmic scale of survival is crucial for his general result that the strength of selection always declines with age. It has been shown [45,46**] that for mutations that modify survival at a different scale, it is easy to construct counterexamples where the force of selection increases with age. Perhaps more importantly in the context of strongly structured social insect colonies, it has been shown that allowing for survival to be condition-dependent in addition to age-dependent also invalidates the rule that the strength of selection declines with age [18].

For social insects, an additional complication arises due to the queen producing offspring that do not reproduce themselves — the workers. As a result, the age of first reproduction beyond which the force of selection drops below its maximal value is not the age of first producing offspring, but the age at first reproduction of sexual offspring (Fig. 1). This is one reason why senescence in social insect queens is expected to be delayed compared to solitary insects with similar age of first breeding. It is still an open question how the force of selection changes with age for workers.

Fig. 1



The force of selection in social insects. The black line represents a hypothetical solitary insect, where the force of selection declines from the age of maturity onwards. A queen in an annual colony (gray line), on the other hand produces workers early in the season, but workers have zero reproductive value since they do not reproduce. Colony maturity is only reached once the colony starts producing sexual offspring at the end of the season (gray line in panel A) leading to an extended period of strong selection that should promote long queen lifespans.

AP. The DS theory focusses on trade-offs implied by the allocation of limited resources to antagonistic physiological processes such as maintenance and reproduction. When applied to social insects, it is sometimes said that the fecundity/longevity trade-off is almost miraculously ‘reversed’ [13] because queens have both increased longevity and increased fecundity when compared to workers or solitary insects. This is somewhat misleading because positive correlations between survival and fecundity have been observed at the between-individual level in many species [30], yet they are easily explained by between-individual variation in resource availability without violating within-individual trade-offs [30] but see the last chapter of this issue for more details. Indeed, social insect queens often have virtually limitless resources due to transfers by workers, thus being ‘liberated’ from their individual trade-off, and this may well be the most important explanation for their extraordinary longevity. At the colony level, queens perform a role analogous to the germ line, while workers may be regarded as the ‘disposable soma’ [21[•],31]. However, to take this further than an interesting metaphor, models should be built that explicitly integrate within-colony resource transfers with individual-level trade-offs. Lee [32] integrated evolutionary aging models with intragenerational and intergenerational resource transfers, generalizing Hamilton’s age-specific force of selection to resource investment in a social context. This model has been used to explain phenomena such as post-reproductive menopause, but has yet to be extended to social insects [33].

Future directions and conclusions

As we have seen, the classical evolutionary theories of aging do not directly apply to eusocial insects. Perhaps most importantly, Hamilton’s age-specific force-of-selection principle no longer applies due to the caste-structure of social insect colonies (Box 1). Moreover, classical theories are focused on trade-offs at the individual level, while trade-offs at the colony level, due to resource transfers between castes, are much more important for highly social insects. Any future evolutionary theory of aging in social insects that takes these factors into account needs to be based at least partially on indirect-fitness arguments, given the different levels of sociality, since otherwise the age-specific effects of mutations in workers cannot not be quantified. Such a theory must also take feedbacks between survival and relatedness into consideration: longer queen survival will often lead to higher within-colony relatedness and less conflict as compared to species where queen turnover can occur, which in turn will affect selection on senescence and, hence, viability. In our opinion, class-structured inclusive fitness models [34–36] are the most promising tools to analyze caste-specific allocation decisions, between-caste resource transfer and their direct and indirect fitness effects.

In addition to extending the evolutionary theories as mentioned above, a complementary approach is to ‘evolutionize’ some of the numerous more mechanistic proximate models of senescence. For example, the reliability theory of aging [37[•],38] may provide a useful causal model of mechanisms that lead to diverging mortality patterns of queens and workers and especially the plastic, state specific response in worker mortality to intrinsic and extrinsic factors at the colony level. By allowing model parameters to have a genetic basis and to be evolvable, the proximate aspects of reliability theory can be integrated with ultimate theories of aging. More generally, it is a challenge to theoretical modelers to incorporate partially overlapping caste-specific regulatory gene networks in their models and to investigate to what extent the mutation accumulation and antagonistic pleiotropy theories can be reconciled with caste-specific aging [39]. In general, aging phenotypes may evolve from the existing regulatory machinery provided by different physiological states in the life cycles of solitary ancestors that can be fine-tuned and lead to the evolution of distinct queen and worker phenotypes as well as the plastic, state specific response in worker mortality [40,41] or for example via gene duplication [42,43]. A general mathematical framework [43] on the evolution of functional specialization and division of labor could be used to understand why evolution favors the evolution different aging phenotypes and explain the uncoupling of individual level trade-offs as a result of functional specialization.

In conclusion, social insects provide fertile ground for many extensions of evolutionary aging theory and new models may well have the potential to provide a new impetus to aging theory in general.

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