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Consumption, Mortality and Life-
history Strategies**

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On the Intertemporal Allocation of Consumption, Mortality and Life-history Strategies

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Abstract

This paper studies the bio-evolutionary origin of time preference. By examining human life-history strategies, it shows that time preference reflects the change in the value of survival, which in turn depends on future reproduction and production. It also demonstrates that our biologically endowed time preference is fully embodied in mortality, is always larger than one, reaches its lowest at around age twenty and increases thereafter. These implications are consistent with empirical findings.

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1 Introduction

Intrinsic human characteristics are the end products of natural selection that have been acquired during the course of evolution. The first study to explicitly formalize this notion in economics is by Hansson and Stuart (1990). They argued that naturally selected preferences are the preferences that maximize fitness and that, in equilibrium, the marginal rate of substitution in utility is equal to the marginal rate of substitution in fitness.

Rogers (1994) applied this idea to explain time preference. He contended that human time preference is also in evolutionary equilibrium and that the rate of time preference is given by the marginal rate of substitution (in fitness) between present and future consumption.

Sozou and Seymour (2003) further examined the relationship between time discounting and fitness by applying a biological framework called life history theory. Their model specifically incorporates the disposable soma theory (Kirkwood 1977; Kirkwood and Rose 1991). In essence, life history theory is an analytical framework to study species-specific life-history strategies, such as the age-trajectory of fertility, the timing of maturity and the age-trajectory of mortality, presuming that these life-history traits are the results of adaptation to a unique environment. The disposable soma theory, in particular, suggests that the optimal strategy is to age, and not to have an indefinite life, in the natural environment in which extrinsic mortality is high. Intuitively, this is because the maintenance of the body competes with immediate reproduction for limited resources. Investing in maintenance to the level of immortality is simply too expensive compared with immediate reproduction.

This could be interpreted that senescence is the result of discounting the future. The future, which is uncertain in nature, is less important than the present in terms of fitness. As a result, fewer resources are allocated for the future, or maintenance of the body, and senescence becomes the optimal life-history strategy. Sozou and Seymour (2003) incorporated this idea and argued that time discounting can be measured by the rate of aging that is given by the sum of mortality rate and the rate of decline in fertility.

Along this line, Chu et al (2008) also examined time preference in the context of life history theory and derives the condition that makes intergenerational transfers advantageous. Other studies that referred to the relationship between life history theory and time preference include Hill (1993) and Robson and Kaplan (2003).

In a similar manner, Acharya and Balvers (2004) viewed time preference as the end product of natural selection, but from a different perspective. They assumed that individuals make their life-cycle consumption choices to maximize life expectancy, presuming that life expectancy would approximately mirror the expected number of offspring. Based on this assumption, they showed that time preference reflects mortality.

This paper follows these studies and examines the relationship between life-history strategies and time preference. Deriving time preference from life-history strategies, however, does not necessarily reject the relationship between time preference and non-biological factors. Social factors such as learning and culture can affect time discounting (Becker and Mulligan 1997). Similarly, it is not surprising if psychological and age-related factors are related to time preference (Trostel and Taylor 2001). In fact, these factors may be regarded as the end-products of life-history strategies. Furthermore, survival is not the only risk factor. This paper aims to assess the bio-evolutionary basis of time preference that may be equivalent to the ‘endowed discount factor’ in the model developed by Becker and Mulligan (1997).

The rest of the paper is organized as follows. Section 2 presents human characteristics in the framework of life history theory in order to establish a common basis to apply life history theory to humans. Section 3 specifies the model and examines human life-history strategies. The main result is that the age-specific mortality rate reflects the value of survival, which in turn depends on future reproductive and productive contributions. Sections 4 and 5 evaluate time preference in the context of life-history strategies. The results indicate that our biologically endowed time preference reflects the change in the value of survival, is fully embodied in mortality, is always positive, reaches its lowest at around age twenty and increases thereafter. These implications are consistent with empirical findings. Section 6 concludes.

2 Life History Theory and Human Traits

Life history theory provides an analytical framework to study the relationship between species-specific life-history strategies (characteristics) and fitness (Gadgil and Bossert 1970). When the population reaches the upper limit of the carrying capacity and remains stationary, the measure of fitness is given by the expected number of offspring (the net reproduction rate) at the beginning of life,

$$F_1 = \sum_{x=1}^{\infty} l_x b_x \quad (1)$$

where l_x is the survival probability up to age x and b_x is the reproductive contribution at age x , with $x \geq 1$ (Taylor et al. 1974).¹ As equation (1) calculates the value of survival in terms of reproduction at birth under stationary population, F_1 is also equivalent with the reproductive value at birth. With the pressure of natural selection, the genotypes and the associated phenotypes (strategies) that generate a higher value of F_1 have spread out and remained in the current population.

¹See e.g. Stearns (1992) for the methods to measure fitness in various environments.

More generally, the reproductive value at age j under stationary population can be written as

$$F_j = \sum_{x=j}^{\infty} \frac{l_x}{l_j} b_x = b_j + \frac{l_{j+1}}{l_j} F_{j+1} \quad (2)$$

where the second equality of equation (2) shows that the reproductive value is the sum of the current and future contributions to reproduction. The relationship between these two terms represents the essence of life history theory, i.e., the trade-off between reproduction and survival (Williams 1966). As both current reproductive contribution, b_j , and the survival probability to the next period, $\frac{l_{j+1}}{l_j}$, depend on the amount of energy allocated, spending more on one means spending less on the other. In other words, immediate reproduction and survival are competing for the same resources.

This trade-off actually represents the trade-off between current and future reproduction. Future reproduction is possible only if the individual survives to the future, and survival is merely a means for future reproduction. Thus, if current reproduction is more important relative to future reproduction, more resources would be allocated to current reproduction and less to survival. The relative importance of current and future reproduction determines the allocation of resources between immediate reproduction and survival.

Applying life history theory to a particular species, the surrounding environment of the species needs to be taken into consideration. In the case of humans, the surrounding environment is considered to be the African savannah, in which humans (the genus *Homo*) existed for most of their two-million-year history. In this environment, humans lived as hunters and gatherers and created their unique society. Most of our intrinsic traits (strategies) that separate us from chimpanzees, our closest living relatives, presumably result from our adaptation to this ancestral environment.

Incorporating the surrounding environment, the mechanism connecting the environment and species-specific characteristics can be examined in the framework of life history theory. For example, Robson and Kaplan (2003) analyzed intelligence in connection with longevity, and showed that these distinctive traits have evolved together as life-history strategies to adapt in African savannahs to gather nutrient-dense food.

The significance of energy transfer between individuals is another example of human characteristics. Obviously, the transfer of energy, or in other words, parental care, allomothering, and cooperative breeding, is not limited to humans. The inter-individual transfer of energy is widely observed across species as kin selection theory (Hamilton 1964) suggests. Intergenerational transfers, in particular, are recognized as a crucial component of life-history strategies in various species (Lee 2003).

Nonetheless, energy transfer is still considered to be one of the most

prominent features of human society. One reason is that the amount of energy transfer among humans is substantial. For example, comparing human hunter-gatherers and chimpanzees, hunter-gatherer men produce twice as much as they consume, whereas chimpanzee males produce just as much, and the surplus of energy of human males is utilized to support reproduction (Kaplan et al. 2000). This shows that the magnitude of energy transfer is one of the prominent features that separates us from chimpanzees.

Another reason that energy transfer among human beings is significant is found in the variety of relationships between the donor and the recipient. Among humans, the relationship of the donor and the recipient of transfer is not limited to a specific relationship. The donor can be a mother, a father, an aged parent, a grandparent, a child, a spouse, a sibling, a relative, or even an unrelated individual. Consequently, the type of the recipient can also be diverse. On the other hand, in most of the other species, the relationship of the donor and the recipient is limited to a particular relationship, such as the mother-offspring relationship in most mammals and inter-sibling relationship among eusocial insects.² Thus, the diversity in relationships between the donor and the recipient is also considered to be one of the distinctive features in humans.

For these reasons, energy transfer is regarded as one of the crucial factors that affect human evolutionary process in a number of studies.³ For example, intergenerational transfers as well as learning play critical roles in promoting the coevolution of intelligence and longevity (Robson and Kaplan 2003). Similarly, the grandmother hypothesis is based on intergenerational transfers made from grandmothers to their daughters and grandchildren (Hawkes 2003).

Nevertheless, the definition of energy transfer is not straightforward. In a broader sense, pregnancy, for example, can be considered to be an intergenerational transfer because the basic necessities for survival are transferred to the unborn offspring from the mother. Generally speaking, however, pregnancy, as well as other energy transfers before birth, is considered to be part of fertility.

To avoid this kind of overlap, energy transfer in this study is defined as the difference between production and consumption as in Kaplan (1994) and Kaplan et al (2000). This indicates that all transfers are in the form of material resources. In other words, as long as transfers are materials, they are not limited to the transfer from parents to offspring, and can be arranged between any types of individuals. In contrast, transfers of a non-material basis are included in reproductive contribution, implying that reproductive contribution covers not only fertility but also the transfer of energy when

²See Carey and Gruenfelder (1997) for the roles of the elderly and intergenerational transfers in other species.

³The mechanism that promotes the evolution of intergenerational transfers is studied by Chu and Lee (2006).

resources are consumed and processed into energy by other individuals. This includes breast-feeding, protection, warmth, and teaching by both parents and non-parents.

The next section presents the model and examines life-history strategies with resource transfers.

3 Optimal Life History

Focusing on life-history events after maturity, let the reproductive contribution of an individual at age x be

$$b_x = A_x V_x^\gamma \quad (3)$$

where A_x is exogenously-determined reproductive efficiency, V_x is the energy contributed to reproduction, and γ is the parameter with $0 < \gamma < 1$. Reproductive efficiency, A_x , represents the productivity connecting energy inputs and reproductive outcome through childbirth and childcare. In general cases, A_x is expected to be higher (more efficient) when the individual is young since it deteriorates with senescence. The parameter γ expresses the degree of concavity of reproductive output, b_x . Since the time that can be allocated for reproduction is not infinite during each period, b_x increases with V_x but at a decreasing rate.

Next, assume that all death at any age occurs at the end of the period and that the age-specific mortality rate is given by

$$m_x = e^{-qW_x} \quad (4)$$

where q is a parameter representing exogenously-given maintenance efficiency and W_x is the energy allocated for survival. Subsequently, given that $e^{-qW_0} = 0$, the survival probability at age x becomes

$$l_x = \prod_{i=0}^{x-1} (1 - e^{-qW_i}). \quad (5)$$

Equation (5) shows that the chance of surviving to the next age is nil at $W_x = 0$ and the chance increases with W_x .

The energy for V_x and W_x is obtained from consumption. At each period, the individual consumes resources and converts them into energy. Then, the energy is physiologically allocated to V_x and W_x .

On the production side, let y_x be the exogenously-given amount of production which can possibly depend on age. Age-dependent factors such as experience, learning and physical strength may affect the amount of production. Assuming that resources cannot be stored and that the members of the

community share resources, the intratemporal aggregate budget constraint of the community is given by

$$\sum_{x=1}^{\infty} l_x (y_x - V_x - W_x) \geq 0. \quad (6)$$

Generally speaking, older individuals transfer resources to younger individuals such as their own children, nieces, and nephews (Lee 1997).

Equation (6) is also the individual's intertemporal budget constraint. Individuals borrow resources from older generations when they are young and their reproductive values are relatively high. Instead, they transfer resources to younger generations later in their lives. It is worth noting that the amount of resources they return exceeds the amount they borrow. This is because they need to pay back for those who died, possibly such as their sisters and brothers. In other words, the community works as the extended family to share mortality risks, and survivors take care of orphans. In this situation, the budget constraint does not necessarily hold at each period at the individual level. Instead, the budget constraint must be met at lifetime level so that the expected lifetime consumption is no more than the expected lifetime income.

Given these conditions, the next step is to solve for the optimal allocation of resources that maximizes the reproductive value, F_1 . Since the problem can be expressed as a simple static optimization problem in which all values are measured at the beginning of the life, the Lagrangian method is applied. Substituting b_x in equation (3) into equation (1) and using equation (6), the Lagrangian is defined as

$$L(V_x, W_x, \phi) = \sum_{x=1}^{\infty} l_x A_x V_x^\gamma + \phi \left[\sum_{x=1}^{\infty} l_x (y_x - V_x - W_x) \right] \quad (7)$$

where ϕ is the Lagrange multiplier. Recalling that $l_x = \prod_{i=0}^{x-1} (1 - e^{-qW_i})$, the first order conditions for any arbitrary age, j , are given by

$$\frac{\partial L}{\partial V_j} = l_j \gamma A_j V_j^{\gamma-1} - \phi l_j = 0, \quad (8)$$

$$\begin{aligned} \frac{\partial L}{\partial W_j} &= \sum_{x=j+1}^{\infty} \prod_{i=0}^{x-1} (1 - e^{-qW_i}) A_x V_x^\gamma \frac{q e^{-qW_j}}{1 - e^{-qW_j}} \\ &+ \phi \sum_{x=j+1}^{\infty} \prod_{i=0}^{x-1} (1 - e^{-qW_i}) (y_x - V_x - W_x) \frac{q e^{-qW_j}}{1 - e^{-qW_j}} \\ &- \phi \prod_{i=0}^{j-1} (1 - e^{-qW_i}) = 0, \end{aligned} \quad (9)$$

To interpret the meaning, these equations are reorganized as follows. First, equation (8) can be rewritten as

$$\gamma A_j V_j^{\gamma-1} = \phi. \quad (10)$$

This indicates that the shadow price is equal to the marginal benefits of immediate reproductive investment and that the marginal benefits of V_x are constant across ages.

Second, equation (9) can be rewritten as

$$qe^{-qW_j} \sum_{x=j+1}^{\infty} \frac{l_x}{l_{j+1}} A_x V_x^\gamma + qe^{-qW_j} \phi \sum_{x=j+1}^{\infty} \frac{l_x}{l_{j+1}} (y_x - V_x - W_x) = \phi, \quad (11)$$

or equivalently,

$$qe^{-qW_j} (F_{j+1} + \phi k_{j+1}) = \phi \quad (12)$$

where F_{j+1} and k_{j+1} are respectively equal to $\sum_{x=j+1}^{\infty} \frac{l_x}{l_{j+1}} A_x V_x^\gamma$, the reproductive value at age $j+1$, and $\sum_{x=j+1}^{\infty} \frac{l_x}{l_{j+1}} (y_x - V_x - W_x)$, the accumulated productive surplus that the individual is expected to obtain at age $j+1$ onwards. Note that F_{j+1} can be interpreted as the value of survival to age $j+1$ in terms of reproduction. This is because the advantage of surviving to age $j+1$ in terms of reproduction is solely expressed in F_{j+1} . Similarly, k_{j+1} can be understood as the value of survival to age $j+1$ in terms of *production*. By surviving to age $j+1$, the individual can acquire this productive surplus. However, obtaining productive surplus itself is not the end. Production is valuable because it can be converted to reproductive contribution. The term ϕ expresses the exchange rate that converts the value of productive surplus into the value of reproductive contribution. Thus, ϕk_{j+1} represents the value of the accumulated productive surplus on reproduction at age $j+1$, and subsequently expresses the value of survival to age $j+1$ in terms of indirect reproductive contribution.

Putting them together, the terms in the parentheses in equation (12), $F_{j+1} + \phi k_{j+1}$, can be interpreted as *the value of survival* that includes both direct (reproductive) and indirect (productive) contributions. By surviving to age $j+1$, the individual currently at age j obtains $F_{j+1} + \phi k_{j+1}$. Therefore, given that qe^{-qW_j} is the marginal effect of W_j on survival, equation (12) shows that the marginal benefit of W_j on reproduction is equal to the cost of spending one unit of resources on W_j which is represented by ϕ . It also indicates that the marginal benefits of W_x are constant across ages.

Finally, equating equations (8) and (9), the relationship between V_j and W_j can be expressed as

$$\gamma A_j V_j^{\gamma-1} = \frac{qe^{-qW_j} F_{j+1}}{1 - qe^{-qW_j} k_{j+1}}. \quad (13)$$

This shows that the marginal effects of reproductive and survival investments must intratemporally be equal.

Equations (10), (12), together with (13) exhibit the optimal life-history strategy, i.e., the age-trajectories of reproductive contribution and survival. In particular, to focus on the age-trajectory of mortality, equation (13) can be rewritten as

$$e^{-qW_j} = \frac{\phi}{q} \frac{1}{F_{j+1} + \phi k_{j+1}}. \quad (14)$$

Equation (14) shows that mortality rate reflects the value of survival, $F_{j+1} + \phi k_{j+1}$, given that ϕ and q are constant. In other words, the change in the value of survival shapes the age-trajectory of mortality.

Now, assume for a moment that A_x and y_x are constant without any biological age limit. In this hypothetical case, age has no meaning but is merely the number of years after birth. Individuals of all ages are basically equipped with the same physiological quality. This implies that the relative importance of the present to the future is constant across ages and that all individuals allocate the resources in the same manner. Thus, in this case, V_x and W_x are constant and the transfer of energy is equal to zero at all ages, indicating that the mortality rate remains constant across ages. Accordingly, F_{x+1} is constant and k_{x+1} is equal to zero for all ages. Namely, individuals do not senesce in this hypothetical situation.

However, age matters to determinate growers, including humans, that stop growing at maturity. Among determinate growers, A_x is expected to decrease with age after maturity. As a result, F_{x+1} often hits its peak at maturity and decrease thereafter. This is the reason that the upward age-trajectory of mortality rates after maturity is the norm among determinate growers. Similarly, the value of k_{x+1} primarily depends on the age-trajectory of y_x . However, the change in k_{x+1} is not straightforward for humans since human productivity increases even after maturity. For example, human productivity in the natural environment is expected to increase until they reach middle age (Kaplan et al. 2000).⁴ This indicates that the change in mortality rate, whether it decreases or increases, depends on the size of the change in ϕk_{x+1} relative to F_{x+1} . If the contribution of the increase in k_{x+1} outweighs the decline in F_{x+1} , mortality rate may decrease, especially in the earlier parts of adulthood.

To examine the significance of the change in y_x as well as other parameters, the age-trajectory of mortality rates is calculated with various sets of parameter values in Figure 1. The results show that, in general, mortality monotonically increases towards the end of the maximum lifespan. The exceptional case is when the gain in productivity is significant enough to offset

⁴Intergenerational transfers are all the more important because the changes in productivity and reproductive value do not move together. If they move in parallel, energy transfers may be simply redundant.

the decline in reproductive contribution. As shown in Figure 1(b), mortality can decrease in the early part of adulthood when the gain in productivity is relatively large.

Place Figure 1 around here

This case is considered to be close to the actual age-trajectory of human mortality in the ancestral environment. For example, the age-specific mortality of the *Ache* people, a hunter-gatherer population in Paraguay, hits its lowest around twenty years of age and continues to rise in the subsequent ages (Hill and Hurtado 1996). Interestingly, the mortality rate still decreases at the age of maturity. Presuming that the age-trajectory of mortality in the ancient environment can be speculated from the ones in recent hunter-gatherer populations, human mortality in the natural environment is expected to hit its lowest around twenty years of age.

4 Resource Allocation and Behavior

It has been shown that the importance of present reproduction relative to future reproduction shapes the age-trajectories of reproductive contribution and mortality, and simultaneously determines the intratemporal and intertemporal allocation of resources. Using these results, the properties of optimal life-history strategies can be examined.

Regarding the intratemporal allocation, crucial properties are summarized in equation (13). The marginal benefits are equal between reproductive and survival investments. However, we, as human, have virtually no means of deliberately controlling the allocation of consumed energy between reproductive contribution and survival since our physiology (the neuroendocrine systems or hormones) regulates the allocation of consumed energy (Finch and Rose 1995). In this aspect, the intratemporal allocation is not related to our behavior. Although we can partly influence the allocation of energy by determining what to consume and how to behave, e.g., by consuming more positional goods to increase the chance of mating instead of consuming foods to raise the chance of survival, or by taking risky actions to attract the members of the opposite sex, the intratemporal allocation of energy depends more on our physiology than on our behavior.

Turning to the intertemporal aspect, the optimal level of consumption, $C_x = V_x + W_x$, is expected to decrease with senescence. This is because V_x is expected to either remain constant or decrease and W_x to decrease with senescence. Therefore, the optimal age-trajectory of consumption becomes decreasing with age unless W_x is increasing rapidly with age.

The intertemporal aspect can be examined further with the marginal rates of substitution between current and future consumption, MRS_x . Let-

ting j be an arbitrary age that corresponds to the current period, MRS_j is given by $-\frac{dC_{j+1}}{dC_j} = \frac{\partial F_j / \partial C_j}{\partial F_j / \partial C_{j+1}}$, and $\frac{\partial F_j}{\partial C_x}$ for $x = j, j + 1$ are given by the marginal benefits of reproductive and survival investments on the reproductive value where

$$\frac{\partial F_j}{\partial V_j} = \gamma A_j V_j^{\gamma-1}, \quad (15)$$

$$\frac{\partial F_j}{\partial V_{j+1}} = \frac{l_{j+1}}{l_j} \gamma A_{j+1} V_{j+1}^{\gamma-1}, \quad (16)$$

$$\frac{\partial F_j}{\partial W_j} = q e^{-qW_j} (F_{j+1} + \phi k_{j+1}), \quad (17)$$

$$\frac{\partial F_j}{\partial W_{j+1}} = \frac{l_{j+1}}{l_j} q e^{-qW_{j+1}} (F_{j+2} + \phi k_{j+2}), \quad (18)$$

for those surviving at age j . As C_x can be allocated to either V_x or W_x , the marginal benefits of reproductive and survival investments on the reproductive value, which are equivalent at optimal, represent the marginal benefit of consumption on the reproductive value.

It is worth noting that the change in W_x affects F_j in two ways. One way is through l_{x+1} . This directly changes the expected reproductive contribution. The other way is through k_{x+1} . The change in W_x indirectly alters reproductive outcomes by influencing the expected productive surplus since additional productive surplus can eventually be converted to consumption and contribute to reproduction.

Thus, MRS_j on the optimal path where marginal benefits of reproductive and survival investments are constant is given by

$$MRS_j = \left(\frac{l_j}{l_{j+1}} \right)^*. \quad (19)$$

Here, the superscript $*$ is added to stress that this is the optimal value that maximizes fitness. Equation (19) shows that, on the optimal path, MRS_j is expressed by the inverse of age-specific survival probability. As it is calculated on the optimal path, consumption is not necessarily constant across ages on the path. It coincides with MRS_j on the constant consumption path when individuals do not senesce.

However, in practice, the intertemporal allocation is not involuntary. It is largely influenced by our behavior since we can deliberately control it by deciding how much to consume at present. Thus, we may possibly behave in a non-optimal way without an appropriate mechanism that coordinates our behavior.

Preferences can serve as the mechanism that coordinates our behavior as our behavior depends on our preferences. In the course of evolution, it is considered that preferences that lead to non-optimal behaviors would have been eliminated and those that generate a higher reproductive value

in the ancient environment have spread out and remained in the current population. The behavior that yielded a higher reproductive value resulted in a higher utility, at least, in the ancient past.

To see this, suppose that individuals are endowed with time-separable lifetime utility function and that each instantaneous utility function reflects the effects of consumption on the reproductive value on the same age. It is worth noting that the reproductive value depends on both reproductive contribution and survival investment. Individuals obtain utility from consumption because it increases current reproductive contribution and survival probability, and consequently contribute to fitness.

This implies that the instantaneous utility function is not necessarily independent of age. As the effects of consumption on the reproductive value depends on age, it is more plausible to assume that the instantaneous utility function changes with age. At the prime of reproductive periods in which resources can be transformed into the reproductive value more efficiently, the same amount of consumption would yield a higher utility. The assumption of the constant instantaneous utility function is reasonable only if individuals do not senesce. Therefore, the lifetime utility function can be written as

$$U = \sum_{x=1}^{\infty} \prod_{i=0}^{x-1} \frac{1}{\beta_i} u(C_x; x). \quad (20)$$

where $u(C_x; x)$ is the instantaneous utility function at age x and β_x is time preference between age x and $x + 1$ which measures the relative importance of $u(C_x; x)$ over $u(C_{x+1}; x + 1)$.⁵ Here, the instantaneous utility function satisfies ordinary properties such as continuity, increasing monotonicity and strict concavity.

Suppose further that the marginal benefits of reproductive and survival investments are correctly translated into the marginal utilities at the fitness-maximizing levels of consumption and that the marginal utilities measured at these levels are constant across ages. This corresponds to the condition that the marginal benefits of reproductive and survival investments are constant across ages on the optimal path. Thus, when the fitness-maximizing level of consumption decreases with senescence, the marginal utilities measured at the constant level of consumption also decline with age.

Next, suppose that individuals can exchange resources with the age-dependent interest rate, R_x , which each individual can not control. Here, the source of interests is mortality risk, and thus, R_x must correspond to

⁵One straightforward example of the instantaneous utility function is

$$u(C_x; x) = A_x V(C_x)^\gamma + \left(1 - e^{-qW(C_x)}\right) (F_{x+1}^* + \phi k_{x+1}^*). \quad (21)$$

given that consumption is physiologically allocated to V and W in an optimal manner so that it satisfies equation (13) with optimal F_{x+1} and k_{x+1} .

the actuarially fair premium. Subsequently, the lifetime budget constraint becomes

$$\sum_{x=1}^{\infty} \prod_{i=0}^{x-1} \frac{1}{R_i} (y_x - C_x) \geq 0. \quad (22)$$

In the context of intergenerational transfers, it is expected that young individuals borrow resources and older individuals return them to young individuals under this budget constraint.

Using these conditions, the optimal allocation of consumption that maximizes utility must satisfy

$$u'(C_x; x) = \frac{1}{\beta_x} R_x u'(C_{x+1}; x+1) \quad (23)$$

where the derivatives are taken for consumption. This is the standard Euler equation expect that instantaneous utilities can possibly be age-dependent.

To achieve the optimum where fitness is maximized, equation (23) must be satisfied with fitness-maximizing level of consumption, C_x^* , for all ages. This also indicates that R_x must be equal to $\left(\frac{l_x}{l_{x+1}}\right)^*$. As R_x corresponds to the actuarially fair premium, it must be equal to the inverse of the conditional survival probability to the next age, $\frac{l_x}{l_{x+1}}$, and it is equal to $\left(\frac{l_x}{l_{x+1}}\right)^*$ when $C_x = C_x^*$.

Considering that the individual is maximizing his/her own lifetime utility, this is possible only if the individual is endowed with an appropriate time preference,⁶

$$\beta_x = \left(\frac{l_x}{l_{x+1}}\right)^*. \quad (24)$$

for all ages. Otherwise, individuals would deviate from the fitness-maximizing trajectory of consumption. Therefore, the endowed time preference must be equal to MRS_x in equation (19) when the utility function correctly reflects the effects of consumption on fitness.

5 Implications

Equation (24) indicates that time preference is fully manifested by mortality. This is not a coincident. As both mortality and time preference reflect the value of survival in the same manner, they are equivalent. Mortality embodies the value of survival at the physiological level and time preference represents it at the behavioral level. To the contrary, other life-history

⁶The individual being endowed with an appropriate time preference is a necessary condition to achieve C_x^* as the utility-maximizing level of consumption. If $\beta_x \neq \beta_x^*$ for any x , the age-trajectory of consumption is not consistent with fitness-maximizing trajectory anymore. It is also sufficient in the long run where only the fitness-maximizing optimum continues to exist.

factors such as a change in reproductive efficiency do not appear in the right-hand side of equation (24), indicating that they do not directly affect time preference. They affect time preference only indirectly through influencing mortality. This is because the transfer of resources absorbs the changes in these factors by equalizing the age-specific marginal benefits of reproductive investment. Without intergenerational transfers, the change in reproductive contribution appears in the right-hand side as in Sozou and Seymour (2003).

Equation (24) also suggests that the age-trajectory of time preference is parallel to that of mortality. Thus, time preference is always larger than one (the rate of time preference is always positive), indicating that present consumption is always more important than future consumption. Furthermore, since time preference is considered to be psychologically set in our minds through the evolutionary process, it is expected that time preference is parallel to the age-trajectory of mortality in the ancient past when we existed as hunters and gatherers, not the age-trajectory of mortality in the current environment. Therefore, our biologically endowed time preference hits its lowest around the age of twenty and increases thereafter, as the Hill and Hurtado (1996) mortality data suggest.

These implications are not novel from empirical perspectives. A number of studies have examined the relationship between age and time preference (Green et al. 1994; Trostel and Taylor 2001; Ventura 2003; Bishai 2004; Read and Read 2004), and Trostel and Taylor (2001) and Read and Read (2004) have found that time preference increases with senescence. The difference between these two studies lies in the age at which time preference is at its lowest. The result of Trostel and Taylor (2001) suggests that time preference continues to increase during adulthood, indicating that it is lowest among individuals in their twenties. On the other hand, in Read and Read (2004), the rate of time preference is lowest among individuals in their forties. The results obtained in this paper are closer to the empirical findings in Trostel and Taylor (2001) although time preference in this study represents only the endowed time preference.

Finally, it is worth discussing that being endowed with an appropriate time preference is not the only solution among a larger set of human behaviors. It is true that an appropriate time preference is necessary if the individual is maximizing his/her own utility. However, if individuals are assumed to possess the ability to share consumption *intratemporally* with others so that the marginal utilities are equal among all the members of the community, it would also generate the fitness-maximizing allocation of consumption. Instead of maximizing their own lifetime utilities, individuals simply share resources in the community so that $u'(C_x; x)$ is equal to $u'(C_{x+1}; x+1)$ under equation (22) which is now regarded as the intratemporal aggregate budget constraint with $\prod_{i=0}^{x-1} R_i = l_x$. Indeed, anthropological studies have shown that the hunter-gatherer populations share food according to their needs (see e.g. Kaplan and Gurven 2005).

When the population is stationary, this allocation strategy is equivalent with the utility-maximizing allocation. Allocating consumption *intratemporally* so that the marginal utilities are equal across individuals within the same period is equivalent to allocating consumption *intertemporally* so that the marginal utilities are constant across ages for the individual. Therefore, if individuals possess the ability to share consumption properly with others, it can also guarantee that consumption is allocated in a fitness-maximizing manner.⁷ Consequently, individuals do not need to take the intertemporal allocation of consumption into consideration, rendering the intertemporal perspective redundant.

In this case, empathy, or more precisely, a set of moral codes built out of empathy (Baron-Cohen 2005), would probably be what drives us to share consumption. Empathy creates affective feelings toward others by allowing the individual to infer, understand, and/or share another's emotional state. In particular, humans, and perhaps apes among primates, are known to have acute cognitive abilities to empathize. These species have the ability to take another's perspective and respond with appropriate emotion without losing self-identity (see e.g. Decety and Jackson 2004; de Waal 2008 for reviews). This ability, called empathic perspective-taking, helps one to understand the other's specific situation and needs, and allows that individual to take other-regarding pro-social behaviors such as food sharing.

Comparing these two mechanisms that enable consumption to be allocated in a fitness-maximizing manner, it is more advantageous to be endowed with time preference if there exist any reasons that require intertemporal consideration. For example, when there is a seasonal or daily variation in the amount of food that individuals can possibly hunt or gather, empathy alone can not adequately cope with this situation. Since smoothening of the actual production level can contribute to one's own reproduction, it is beneficial to have time preference.

Nevertheless, the relationship between time preference and empathy may not be so simple. As discussed in psychological literature, they might be related at their origins (Posner 1995; Frederick 2003; Pronin et al. 2008). According to these studies, the present self and the future selves are virtually separate persons, and time preference is the reflection of the importance of the present self relative to the future selves. In particular, the experiments in Pronin et al (2008) showed that the decisions people make for the future selves and other people are similar. In this context, time preference can be interpreted as one form of empathy, empathy to the future selves. The value of the present self relative to the future selves with appropriate discounting factors yields the optimal rate of time preference. In this regard, empathy

⁷The possibility that other equilibria that satisfy $u'(C_x, x) = u'(C_{x+1}, x+1)$ with non-fitness-maximizing level of consumption accidentally exist can not be excluded in the short run. However, these equilibria would be eliminated in the long run where the force of natural selection is strong.

is considered to be the root of time preference (see Frederick 2003 for more details).

6 Concluding Remarks

The purpose of this paper is to understand the mechanism regulating our intertemporal choices. To do this, it examines human life-history strategies and demonstrates that time preference reflects the change in the value of survival.

The results support the idea that mortality and time preference are two sides of the same coin. The coin is the value of survival. Mortality embodies it at the physiological level and time preference represents it at the behavioral level. Since the study of Yaari (1965), mortality has been considered to be one of the components that cause discounting. However, mortality is not merely one of the components, but is the reflection of time preference. It is true that “the future is discounted because survival is uncertain” (Yaari 1965). Yet, the opposite is also true that “survival is more uncertain because the future is discounted.”

Consequently, the traditional view that time preference is something unfavorable needs to be revised. Time preference is often seen as a weakness or cognitive deficiency, and is often ascribed to impatience, shortsightedness, myopia or irrationality. Therefore, studies that aim to explain time preference tend to look for the causes of irrationality and ask why we are not perfect. However, as discussed in this paper, time preference is not a deficiency, but is an optimal trait that was acquired during the course of evolution. Our surrounding environment has changed since then and the rate of time preference embedded in us may not exactly be optimal any more. However, being too patient is not optimal either.

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Fig. 1. Age-trajectories of Mortality Rate. (a) The effects of changes in parameter values. (b) The effects of the change in y (The values of y between ages 1 and 10 are respectively equal to 2, 4, 6, 6, 6, 6, 6, 6, 4, 2). To construct the figures, lifespan is divided into ten age-classes, one age-class corresponding to five years, assuming that the age of maturity is 15 years old and that the maximum lifespan is 65 years old. Limiting the maximum lifespan to 65 years is merely for simplicity. As for A_x , it is assumed to follow the equation $A_{x+1} = A_x/(1 + a)$ with $a \geq 0$ until the 10th age-class and be equal to zero in the 11th age-class onwards. This indicates that any individual would certainly die in the 11th age-class because the value of survival for one's own reproductive contribution reaches 0. Furthermore, as A is the efficiency parameter that reflects both childbirth and childcare, it is not expected to decrease rapidly. There is no theoretical or empirical basis for these parameter values.

