Determinants of Time Allocation across the Lifespan

A Theoretical Model and an Application to the Machiguenga and Piro of Peru

Michael Gurven
University of California, Santa Barbara

Hillard Kaplan
University of New Mexico

This paper lays the groundwork for a theory of time allocation across the life course, based on the idea that strength and skill vary as a function of age, and that return rates for different activities vary as a function of the combination of strength and skills involved in performing those tasks. We apply the model to traditional human subsistence patterns. The model predicts that young children engage most heavily in low-strength/low-skill activities, middle-aged adults in high-strength/high-skill activities, and older adults in low-strength/high-skill activities. Tests among Machiguenga and Piro forager-horticulturalists of southeastern Peru show that males and females focus on low-strength/low-skill tasks early in life (domestic tasks and several forms of fishing), switch to higher-strength/higher-skill activities in their twenties and thirties (hunting, fishing, and gardening for males; fishing and gardening for females), and shift focus to high-skill activities late in life (manufacture/repair, food processing).

KEY WORDS: Behavioral ecology; Family; Hunter-gatherers; Life history theory; Time allocation

The allocation of time to alternative activities is a topic that has interested scholars in many different disciplines, such as anthropology, economics, sociology, psychology, and biology. The reason for this interest is that time allocation decisions are fundamental components of life strategies: time is used to accomplish

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Address all correspondence to Michael Gurven, Department of Anthropology, University of California, Santa Barbara, Santa Barbara, CA 93106. Email. gurven@anth.ucsb.edu, hkaplan@unm.edu

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goals, and alternative time profiles may be associated with very different outcomes among both human and nonhuman organisms. Time spent foraging for food results in energy capture but often incurs high risks of mortality owing to predation and accidents. Time spent caring for infants may increase their chances of survival but may also decrease energy available for promoting their growth (Hurtado et al. 1985, 1992).

The critical feature of time allocation decisions is that they involve trade-offs in which the benefits generated (e.g., food energy, infant safety) are balanced by both direct costs (e.g., energy expended, risk of predation) and opportunity costs (Hames 1992). Opportunity costs derive from the fact that time is a limited resource, and as a result, time spent in one activity reduces time available for other activities. Thus the total effects of time allocation decisions not only depend on the costs and benefits of time invested in single activities, but also on the forgone benefits of time spent in other activities. Since time allocation decisions may have direct impacts on an organism's fitness, natural selection is likely to act on the psychological and physiological mechanisms underlying time allocation decisions, especially regarding activities geared towards obtaining food resources, finding mates, provisioning offspring, forming and maintaining alliances, and defending against predators (Hames 1992).

A second critical domain of an organism's life strategy that involves time is the timing of life events. The field of life history theory in biology was developed to explain the timing of life events, with a particular focus on age-schedules of fertility and mortality (Charnov 1993; Roff 1992; Stearns 1992). Components of an organism's life history include gestation length prior to birth, the growth rates of different organs before birth, the length and rate of growth after birth, risks of mortality at each age prior to and after birth, age of first reproduction, reproductive rate and litter size, energy and time invested in each offspring, the timing and effort allocated to intra-sexual competitive behavior, rates of senescence for different organ systems, and increases in mortality rates with age during the adult period.

Compared with their closest primate relatives, humans display some very distinctive life history characteristics (Blurton Jones and Marlowe 2002; Bock and Sellen 2002; Kaplan 1997; Kaplan et al. 2000; Tooby and DeVore 1987). Their brains grow much faster, and for a much longer period of time after birth. Following infancy, they grow relatively slowly until their adolescent growth spurt, and they grow for a longer period of time. Age of first reproduction is delayed and the expected adult lifespan is significantly extended. Food is transferred not only from parents to offspring, but often across three generations, with grandparents providing food and other services for grandoffspring. In recent years, several new theories of human life history evolution have been presented in order to explain some or all of these life history characteristics. Two of those theories, sometimes referred to as the Grandmother Hypothesis (e.g., Hawkes et al. 1998) and the Embodied Capital Theory (e.g., Kaplan 1997) of life history evolution, are a central focus of this paper because they generate a series of competing empirical predictions, particularly with respect to relative importance of body size vs. learned skills in time allocation and life history decisions.

This paper has two goals. The first is to examine the relationship between time allocation decisions and life history strategies and, in so doing, contribute to a growing body of theory on time allocation and work effort across the life course. The second is to apply that framework to explain time spent in alternative activities by individuals living in traditional, small-scale societies and to evaluate empirically the alternative predictions of the life history theories mentioned above, with analysis of data from two native South American populations, the Machiguenga and Piro of southeastern Peru.

The paper begins with a brief review of existing cross-cultural research on time allocation. This is followed by a discussion of the grandmother hypothesis and embodied capital theory. This discussion includes a detailed treatment of Bock's extensions of embodied capital theory, since the formal theory we present and the empirical analyses build directly upon those insights. The theory section then outlines the essential elements of Becker's theory of time allocation (e.g., Becker 1991: chapters 1 and 2), upon which our model builds. It then develops the necessary modifications of his theory for generating a life history approach to time allocation in traditional subsistence societies.

The second part of the paper presents the empirical application of the model. It begins with a brief introduction to the Machiguenga and Piro study populations, and a description of the methodology employed for data collection and analysis. The empirical results follow. Some questions addressed are: (*a*) Do the strength and skill requirements for different tasks determine which age and sex classes perform them most often? (*b*) At what ages do return rates and time allocated to given activities peak? (*c*) What factors influence rates of ascent to the peak and rates of decline from the peak? (*d*) What is the relationship between changes in time investment in activities and rates of return from engaging in those activities? The paper concludes with a discussion of the results and their implications for the evaluation of the two alternative life history theories.

TIME ALLOCATION RESEARCH

There is a great deal of descriptive anthropological data on time allocation in different cultures, especially for specific age and/or sex classes of individuals (e.g., Draper 1975; Hames 1989, 1992; Johnson 1975; Munroe et al. 1983; see also the HRAF Time Allocation series). There have also been several attempts to explain time allocation decisions within or among cultures. Many of these studies focus on environmental or ecological change and its impacts on time allocation (e.g., Hames 1979; Hurtado and Hill 1990; Kelly 1983; Kumar and Hotchkiss 1988; Tiefanthaler 1997). For example, several studies focus on the impacts of technology on production, such as shotguns for improving hunting efficiency (Hames 1979; Kelly 1983) and steel tools on horticultural efficiency (Hurtado and Hill 1990; Salisbury 1962).

With respect to individual variation within cultures, there has been debate among anthropologists regarding the impacts of efficiency on time allocation (Hames 1992; Hawkes et al. 1985; Smith 1987; Winterhalder 1983). According to one view, sometimes referred to as resource maximization, increases in productivity in some activity (mediated either by improvements in technology or by individual differences in ability) should be associated with increased time allocated to that activity. According to the view of time minimization, increased efficiency should reduce time allocation to that activity in favor of other activities. From economic theory, it is clear that time minimization and resource maximization are not opposing strategies, since any problem can easily be transformed from profit maximization to cost minimization and vice versa. The critical issue depends on the shape of the gains curves of the focal activity and of other forgone activities, which cannot be determined from theoretical first principles (Smith 1987) and depend on both substitution and income effects. When trade exists or when social groups, such as households or bands, share the proceeds of work, the theory of comparative advantage predicts specialization, with individuals specializing in the activity at which they are most efficient (Becker 1991: chapter 2). On the other hand, if the values of the commodities produced by activities exhibit diminishing returns, specialization is limited by the extent of the market (Becker 1991). For example, when shotguns increase hunting return rates for the whole group and meat is not traded, more meat may be consumed but less time may be allocated to hunting in favor of other activities.

Time allocation among children has also received considerable attention. Early work by Cain (1977) and Nag and colleagues (1977) showed that, among peasant farmers, children over the age of 10 often work long hours. Those results were used to argue that children in traditional, pre–demographic transition societies were net economic assets to parents (Cain 1981), and as a result, high fertility was an economically rational response of parents (Caldwell 1982). A series of recent studies, however, casts considerable doubt on this theory (Kaplan 1994; Kramer 2002). Although resources flow in both directions between generations, net flows are from parents to offspring and from grandparents to grandoffspring (Kaplan 1994), as would be expected by evolutionary models of parental investment (Turke 1991). In fact, in a large review of research conducted in a broad range of societies, Lee (1996) finds no evidence that the net flow of resources is from children to parents.[1]

Although, on average, children are not net economic assets to parents, there does appear to be considerable cross-cultural variation in their contributions to subsistence work. Draper's (1975) original analysis of children's time allocation among !Kung (Ju/'hoansi) foragers in Botswana showed very low levels of productive work before age 15. Data on calories produced vs. calories consumed among Ache foragers and Machiguenga and Piro forager-horticulturalists in South America yielded similar findings (Kaplan 1994). Those results contrast sharply with the findings from research with peasant farmers, cited above. However, even among and within foraging societies, there is considerable variation in children's work effort. For example, Hadza children in Tanzania, especially in certain seasons, produce a great deal more than !Kung children in bush camps do (Blurton Jones et al. 1994).

Three factors, taken together, appear to explain a significant proportion of this variation. One factor is the risks associated with foraging for young individuals (Blurton Jones et al. 1994; Janson and Van Schaik 1993). The dangers associated with children's work effort vary socioecologically. For example, resources tended to be located at considerable distance from camps among the !Kung, and parents actively discouraged children from traveling outside of camp for fear that they would get lost and be attacked by animals. Among the Hadza, food resources were often located very close to camp, especially during fruit seasons when children were especially productive (Blurton Jones et al. 1994; Janson and Van Schaik 1993).

A second factor concerns the relative productivity of children's labor. Subsistence labor in farming societies, for example, includes many chores, such as harvesting, grain processing, and domestic animal care, that can be accomplished by children (Bock 2002a; Kramer 2002), whereas among foraging societies children are relatively less productive per time spent working in the acquisition of most foods. Seasonal variation in productivity within foraging societies also appears to be explained by relative productivity. When fruits, which are relatively easy for children to forage, are in season, children among both the Ache and Hadza acquire many more calories than when extracted foods, such as roots and palm fiber, are the principal plant food staples (Blurton Jones et al. 1994; Kaplan 1997).

A third factor concerns trade-offs between current and future productivity (Bock 2002a, 2002b; Kaplan 1996; Kaplan and Robson 2002; Kaplan et al. 2000). For example, child labor laws exist in modern societies to ensure that children attend school.[2] School attendance increases future income, but it entails opportunity costs in terms of forgone income. Even in transitional and traditional societies, such trade-offs exist. Bock (2002b) shows that school attendance in transitional villages in Botswana, where children still engage in traditional subsistence labor, depends on familial labor needs, the availability of substitute laborers, and familial wealth. Moreover, children in traditional subsistence societies often engage in play (play hunting, play food processing, etc.) instead of actual, productive work. Presumably such play is safer and imparts more skills that will increase productivity in the future than would time spent in directly productive tasks (Bock 2002b; Caro 1988; Fagen 1981).

TWO ALTERNATIVE MODELS OF THE HUMAN LIFE COURSE

While there is general agreement that socioecological variation explains much of this cross-cultural variation in children's work, there is also considerable debate about the underlying causes of age profiles of both work effort and productivity across the lifespan. This debate grows out of alternative theoretical models of the evolution of the human life course, and particularly about the length of the childhood period. In fact, a recent issue of this journal (2002, Vol. 13, No. 2) was dedicated to presenting those alternative models and to evaluating the existing evidence that bears on the debate.

The Grandmother Hypothesis

According to the grandmother hypothesis, based on a mammalian model of life history evolution developed by Charnov (1993), body size is the primary determining factor in age profiles of productivity (Bird and Bliege Bird 2002; Bliege Bird and Bird 2002; Blurton Jones and Marlowe 2002; Hawkes 2003). The productivity of children is low in many small-scale subsistence societies because the exploitation of most resources consumed by foragers is strength-intensive, and human growth is particularly slow. The length of the juvenile period is determined by a trade-off between physical growth, which increases future productivity and hence reproductive rates, and the probability of reaching adulthood when reproduction begins (Charnov 1993). Exogenous variation in mortality rates determines the nature of this trade-off. When mortality rates are low, additional time spent growing has a small impact on the probability of reaching adulthood, and vice versa when mortality rates are high. Therefore, all else being constant, the length of the juvenile period varies negatively with mortality rates during the late stage of juvenile growth (i.e., the stage after infancy and weaning when mortality rates are particularly high).

The human juvenile period is exceptionally long (18–20 years) because human mortality rates are exceptionally low, even after controlling for overall body size. Proponents of the grandmother hypothesis also argue that in addition to extrinsic factors that reduce human mortality rates, natural selection has acted to reduce human mortality rates in response to the payoffs to grandmaternal investment (Blurton Jones and Marlowe 2002; Hawkes and Bliege Bird 2002; Hawkes et al. 1998). Since extractive foraging is strength-intensive, and as a result, children are not very productive, grandmothers can greatly assist their daughters in raising their offspring through their gathering activities. This increased ability to help generated selection for older women's ability to work hard, increased longevity, and further reductions in mortality rates, which, in turn, selected for an elongation of the juvenile growth period.

Embodied Capital Theory

An alternative view emphasizes the brain, and the skill—and knowledge-intensiveness of the human foraging niche. One specific proposal, which is further developed in this paper, is the embodied capital theory of life history evolution (Bock 2002a, 2002b; Kaplan and Robson 2002; Kaplan et al. 2000, 2003; Robson and Kaplan 2003). According to this theoretical framework, organisms utilize time and energy to invest in the production of alternative forms of somatic or embodied capital. In a physical sense, embodied capital is organized somatic tissue—muscles, digestive organs, brains, etc. In a functional sense, embodied capital includes strength, speed, immune function, skill, knowledge, and other abilities. Since such stocks tend to depreciate with time, allocations to maintenance can also be seen as investments in embodied capital.

Investments in embodied capital, which impact future productivity and future survival, trade off against allocations to current reproduction. The theory is that the distinctive characteristics of human life histories are the result of selection for extreme investments in neural capital and the abilities to learn and process information that the neural capital supports. The shift among our hominid ancestors to a learning-intensive foraging strategy and a diet composed mainly of high-quality, difficult-to-acquire foods generates selection for an extension of the lifespan, increased brain size, and a longer developmental period. The theory argues that (*a*) high levels of knowledge, skill, coordination, and strength are required to exploit the suite of high-quality, difficult-to-acquire resources humans consume; (*b*) the attainment of those abilities requires time and a significant commitment to development; (*c*) this extended learning phase during which productivity is low is compensated for by higher productivity during the adult period, with an intergenerational flow of food from old to young; and (*d*) since productivity increases with age, the time investment in skill acquisition and knowledge leads to selection for lowered mortality rates and greater longevity because the returns on the investments in development occur at older ages.[3] Thus the proposal is that the long human lifespan co-evolved with the lengthening of the juvenile period, increased brain capacities for information processing and storage, and intergenerational resource flows—all in response to, and as supports of, the dietary shift.

Extensions of Embodied Capital Theory to Time Allocation

In a series of papers, Bock (2002a, 2002b, 2004a, 2004b) along with Johnson (Bock and Johnson 2004; Johnson and Bock 2004) extended embodied capital theory in two important ways, upon which the present analysis builds. First, those papers apply embodied capital theory to time allocation over the life course, with a specific focus on childhood. Bock (1995, 2002a, 2002b) hypothesized that time allocation to activities should reflect differential skill and strength as a function of age, and labor substitution among family members. Given that both body size and experience-based skills and knowledge change with age, families will be composed of individuals with different levels of growth—and experience-based capital. Since different tasks in household production require differing degrees of strength and skill, an efficient division of labor in families will allocate tasks so that less skilled and smaller individuals will perform tasks requiring the least skill and strength, and vice versa. He also hypothesized that, in addition to the efficient pattern of labor substitution across family members, children will engage in tasks that provide learning experiences, first through play and later through learning by doing. Such time allocation to learning is an investment in future production. These hypotheses were largely supported in his analysis of time allocation in a rural subsistence village in Botswana (Bock 2002a, 2002b; see also Bock and Johnson 2004 and Johnson and Bock 2004 for comparative application of this approach to intervillage variation and to learning in baboons).

A second extension was to model the interplay of growth and experience (Bock 2004b). He proposes a "punctuated development" model to account for both the rate at which return rates for different activities change with age and changing patterns of time allocation with age. When bodies are small, they will be inefficient at performing most tasks, so most skill acquisition will occur through play, which is much safer. However, as bodies become larger, there will be some immediate returns from actually performing the task, so skills can be most efficiently learned through performance. It is at this point that time allocation to the task will increase dramatically and return rates will correspondingly climb rapidly as experience with the task increases. This pattern will give rise to a punctuated pattern of development in which rates of return show periods of steep increase.

We build on both these insights in the formal model and in the empirical application. Our model extends this reasoning to time allocation across three generations of family members, including older people whose strength, but not knowledge, has declined with age. We also differ in one respect. We suggest that the punctuated development model is most applicable for activities requiring lesser amounts of skill, and that highly skilled activities will exhibit a much longer period of increasing efficiency.

Alternative Implications of the Grandmother and Embodied Capital Theories

The two theories differ in two major ways. The first difference concerns the factors that affect differences in productivity by age. The grandmother hypothesis assumes that the principal factor that differentiates adults and children is their relative body size and the strength advantages that a larger body confers. In contrast, the embodied capital theory proposes that learning is key to the differences in productivity by age. In fact, it proposes that slow physical growth rates in humans result from selection for energy conservation; children's bodies do not grow to adult size until their brains have learned enough to safely and efficiently harvest the difficult-to-acquire resources that humans exploit. This is not to say that strength is irrelevant to productivity, but rather that it must be combined with knowledge in order to be useful in the acquisition of many resources (Bock 2002a, 2002b).

The second difference concerns the relative roles of males and females in the energetics of reproduction, and in the life history adaptation. According to the grandmother hypothesis, it is primarily women who are involved in the care and provisioning of their biological offspring. Selection for lengthening the human lifespan occurred because strong grandmothers could help their daughters raise offspring, who are dependent for some time. Although it is not explicitly stated, the model seems to imply a shift from a combination of childcare and strength-intensive production among reproductive-age women to a greater emphasis on production among postreproductive women. In that model, men hunt to display their quality as mates, but not to provision their own offspring. Any provisioning done by men is viewed as unnecessary for supporting the important human life history shifts discussed above. The model is therefore silent about life course changes in men's time allocation and on the length of the adult lifespan among men. The embodied capital theory proposes that both men and women invest in skill-intensive activities that complement one another, with women investing in extractive foraging and childrearing skills, and men investing in hunting and activities that involve strength and knowledge. Selection on the lifespan favored increased longevity.

These differences between the two theories generate alternative predictions about time allocation over the life course. The next section develops the theoretical and empirical models that will be used to test those predictions.

THEORY

A Lifecourse Perspective on Time Allocation

Following Becker (1991), an optimality approach to time allocation begins with the working assumption that individuals allocate their time so as to maximize utility (in the case of economic models) or fitness (in the case of biological models). In both economic and biological models, it is generally assumed that the gains from some or all activities have a nonlinear correlation with amount of time allocated to them, such that at some point additional increments of time yield diminishing returns. As the payoffs from one activity diminish, allocation of time to some other activity is more profitable. The fundamental prediction is that at the optimal mix of time spent at each activity, the marginal returns from time allocated to all activities will be equal. That is, the gains from an additional small increment of time spent at each activity will be the same for all activities. If, given some time allocation strategy, there is an activity, j, that yields higher marginal gains than some other activity, k, then a net improvement could be derived from increasing time spent at j and decreasing time spent in activity k. From an economic perspective, it is assumed that rational individuals will continue this process until no further changes will yield a net increase in utility. At this optimum, marginal gains in utility, U, from all activities (j) are equal:

$$\partial U / \partial t_j = \partial U / \partial t_j \ldots \partial U / \partial t_z \qquad [1]$$

The reasoning from evolutionary biology is somewhat more complicated. Whereas economic models assume rationality solely on the basis of its heuristic value, evolutionary models posit that natural selection has acted on time allocation decisions through the underlying mechanisms that generate those decisions. Whatever the specific nature of those mechanisms (e.g., foraging stimulated by hunger in response to some physiological state), variation in the specific design of those mechanisms is subject to selection. Those design features associated with the highest fitness become prevalent over time. This reasoning leads to the similar prediction that, at the optimum, the marginal gains in *fitness, W,* from all activities are equal:

$$\partial W / \partial t_j = \partial W / \partial t_j ... \partial W / \partial t_z \qquad [2]$$

A life course perspective on time allocation adds a new dimension to the optimality analysis. Activities may be characterized in terms of both their immediate costs and benefits and their impacts on future payoffs. It is often the case that current and future payoffs trade off against one another. Some activities, especially those involving learning-by-doing, skill development, and formal education, provide little or no immediate benefits but increase rates of return to activities in the future. Other activities, especially those associated with danger, may provide immediate returns but also entail a risk of mortality or morbidity that compromises future payoffs.

Becker (1991) provides a life course model of time allocation that explicitly analyzes some of those trade-offs. In this model, the optimal time allocation program maximizes utility over the life course through the consumption of *commodities.* Lifetime utility is composed of a time series of consumption bundles of *commodities.* Commodities, such as children, health, and prestige, are produced by combining goods with time. For example, wages may be used to purchase food, which, in turn, is combined with cooking and eating time to produce nutritional status and culinary pleasure. Thus, we have $U = U(Z_{11},...Z_{1n},...Z_{m1},...Z_{mn})$, where Z_{ij} is the consumption of the i^{th} commodity at the j^{th} age, and n is the length of life, which is treated as a given. At each age, time and goods are allocated to producing the optimal mix of commodities to maximize utility.

At the same time, however, some time and goods may be allocated to investments in *human capital.* Human capital is a set of attributes, such as skill, knowledge, and health status, that affect the return rates associated with activities. Becker's model, particularly tailored to modern economies, distinguishes two effects of human capital, one that impacts wage rates and another that impacts household production (i.e., cooking, care of children, and other things done at home). Time spent in school, for example, provides no immediate material benefits, entails opportunity costs in terms of lost time in employed work, and may involve direct costs, such as tuition and fees. However, time allocated to schooling increases future wage rates and may also increase future returns to household production, especially with respect to childrearing. Thus, three types of time may be distinguished: wage-related employment, t_w; household production, t_h; and human capital investments, t_q.

The fundamental trade-off is between present and future productivity. Investments in human capital increase future wages and the efficiency of time in the future but decrease current production. At the optimum, the marginal cost of an additional unit of human capital investment must be equal to its future benefits. This means that the change in capital produced by an investment of time or energy multiplied by the effect of that capital on future production, summed over the life course (discounted by the interest rate), must equal the present costs of investments. Again, if the costs were lower than the benefits, it would pay to invest more, and vice versa if the costs were greater than the benefits. One major qualitative conclusion of Becker's model is that, other things being equal, investments in human capital should be greatest early in life and decrease with age. This is because the returns from those investments accrue over time. For example, investments in education increase wage rates over all remaining years of paid employment. An additional year of schooling at age 18 will produce greater payoffs than one at age 60, just before retirement.

Several modifications to this model are necessary for an adequate analysis of time allocation in traditional subsistence societies. First, wage labor is largely irrelevant, and therefore it is necessary to disaggregate household production into alternative activities. Second, it is necessary to replace wage rates with *return rates* (work accomplished per unit of time investment) for each activity and to determine how those return rates change with age as a function of investments in human capital. Third, in order to evaluate the two alternative theories of life history evolution, it is necessary to model the relative impacts of strength and learned skills (what Bock [2002a] calls *growth-based* and *experience-based capital*) on return rates and how changes in strength and skill over the life course should affect time allocation. Fourth, it is necessary to take into account the resource flows across three generations, and labor substitution among individuals of different ages, sexes, and reproductive states.

Our approach is first to model how strength and learned skills are likely to change over the life course. The next step is to present a model of the relative impacts of strength and skill on return rates for different activities. The third step is to model time allocation over the life course as a function of changes in return rates and other age-related factors, such as the value of learning, presence of infants, and inter-individual labor substitution across ages. Each of these steps generates empirical tests that are examined with data on return rates and time allocation among the Machiguenga and Piro.

Strength and Skill as a Function of Age

For the purposes of this analysis, we do not model the action of natural selection on growth and learning; rather we assume that age-profiles of physical growth and knowledge are given exogenously. Denote $s_i(x)$ as "strength" (which includes muscular strength, endurance, agility, and cardiovascular fitness) and $k_i(x)$ as "knowledge" (which includes the general and specific skills and knowledge necessary to complete each task) of individual *i* at age *x*. Even though we define these as unitary functions, each represents a multidimensional growth process. In general, we expect $s_i(x)$ to increase exponentially until about age 20–25, then decrease at an increasing rate for men and women (see Figure 1). Similarly, $k_i(x)$ should also increase exponentially to a given age specific to each task, then increase at a decreasing rate until death (Figure 1). There might be a decline at advanced ages owing to skill loss that is dependent on strength (e.g., dexterity). The functional form used to generate these curves is

$$s_i(\text{age}) = A_1 \times \text{age}_i^{b_1} \times e^{b_2\,\text{age}} \quad [3]$$

and

$$k_i(\text{age}) = A_2 \times \text{age}_i^{b_3} \times e^{b_4\,\text{age}} \quad [4]$$

We estimate the function relating strength to age as

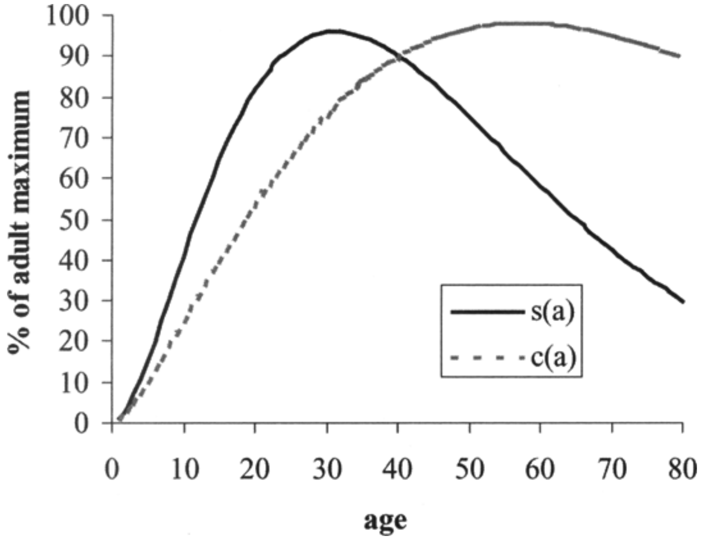
$$s_i(\text{age}) = \text{age}^{1.87} e^{-.06 \times \text{age}} \quad [5]$$

This function corresponds closely to the empirical relationship estimated by Walker et al. (2002) for Ache men, although they used a somewhat different function. Less is known about how knowledge and skill increase with age, but previous research (Kaplan et al. 2000; Walker et al. 2002) suggests that it increases more slowly than strength. Both strength and skill can be expected to increase or decrease based on the kinds of activities individuals engage in, and thus are not just extrinsic functions of age, even though we model them this way. Moreover, we expect skills to increase for a longer period of time owing to "on-the-job" learning, and only to decrease slowly at advanced ages. We estimate the knowledge function as

$$k_i(\text{age}) = \text{age}^{1.5} e^{-.026 \times \text{age}} \quad [6]$$

This function is qualitatively similar to wage functions for highly educated workers. Figure 1 illustrates the two functions.

Figure 1. Strength (s) and skills (c), by age (a) over the lifespan. Strength and skills are represented here as standardized to a hypothetical maximal adult level. See text for parameterization of both curves.



Return Rates as a Function of Age

The next step is to model the effects of $s_i(x)$ and $k_i(x)$ on return rates for different activities as a function of age. The key idea here is that the relative impacts of strength and knowledge on rates of return will vary from activity to activity. Define the rate of return for activity *j* by individual *i* as some function of strength and skills: $R_{ij}(\text{age}) = Fj[s_i(\text{age}), k_i(\text{age})]$. The function F_j maps age-specific strength and knowledge to the rate of return for activity *j* and is assumed to vary from activity to activity. For example, some activities, such as cooking manioc, require little strength and skill, whereas others, such as felling large trees for a garden, require high levels of both. Therefore, in the case of cooking, even though a 22-year-old man possesses greater strength than a 12-year-old girl, both possess enough strength to realize similar return rates, yet their respective return rates for tree felling would be quite different.

One simple function commonly used by economists to model the effects of two inputs in a production process is the Cobb-Douglas function (Nerlove 1965). Since the impacts of strength and knowledge may vary across activities, we write:

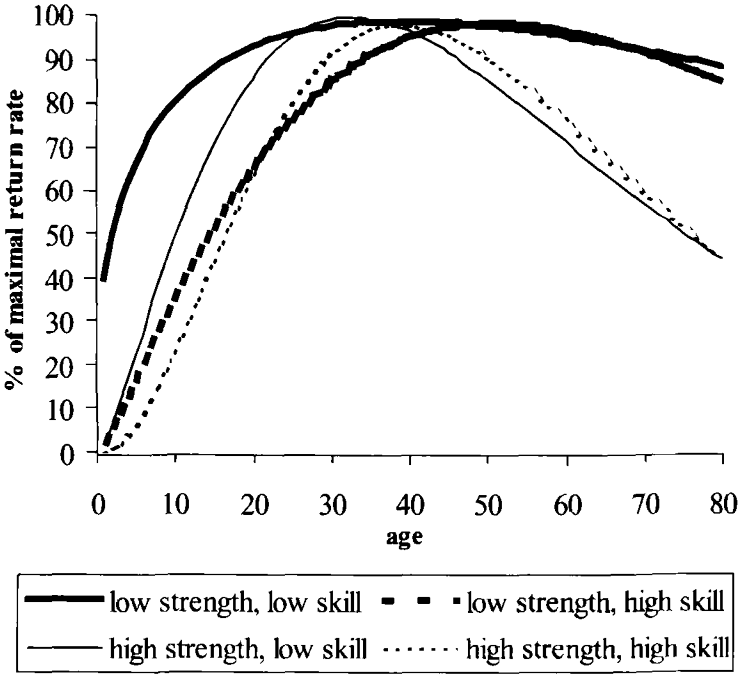
$$R_{ij}(\text{age}) = s_i(\text{age})^{\alpha_j} \times k_i(\text{age})^{\beta_j} \qquad [7]$$

By substituting equations 3 and 4 into equation 7, the following reduced form is obtained:

$$R_{ij}(\text{age}) = A(\text{age}_i^{m_i} e^{n_j \text{age}_i}) \qquad [8]$$

where $A = A_1^{\alpha} A_2^{\beta}$, $m = b_1\alpha + b_3\beta$, and $n = b_2\alpha + b_4\beta$. Although α and β can be thought of as varying continuously and having specific values for each individual activity, it is also useful to consider four classes of activities for both conceptual reasons and for the empirical application: (*a*) low strength/low skill; (*b*) high strength/low skill; (*c*) low strength/high skill; and (*d*) high strength/high skill. By definition, α should be relatively small for low-strength activities and high for high-strength activities, whereas β will be relatively small for low-skill activities and high for high-skill activities. Using the functional forms in equations 3 and 4, with $A_1 = A_2 = 1$, $b_1 = 1.87 > b_3 = 1.5$, and $-b_2 = .06 > -b_4 = .026$, the estimates of *m* and *n* should be relatively small for low-strength/low-skill activities, intermediate-low for low-strength/high-skill activities, intermediate-high for high-strength/low-skill activities, and high for high-strength/high-skill activities. Conversely, estimates of *A* should be relatively large for low-strength/low-skill activities (since return rates should be near the peak even at young ages), intermediate-low for low-strength/high-skill activities, intermediate-high for high-strength/low-skill activities, and lowest for high-strength/high-skill activities. Figure 2 shows the expected return rate for low—and high-strength activities as skill requirements vary, and for low—and high-skill activities as strength requirements vary.[4] The rate of ascent toward peak productivity is greatest for the low-strength/low-skill tasks and slowest for the low-strength/high-skill tasks. There should be a fairly steep decline from the peak return rate for

Figure 2. Caloric return rates as a function of strength and skill, $f[s(a), c(a)]$. Bold lines refer to low-strength activities, thin lines to high-strength activities. Solid lines refer to low skill activities, and dashed lines to high-skill activities. Curves are shown as standardized to a maximal adult level. See text for paramaterization of curves.



high-strength tasks, whereas return rates for low-strength tasks should either asymptote or decline slightly, regardless of skill. Peak productivity should be later for the low-strength/high-skill than for high-strength/low-skill tasks, if skill increases more slowly than strength. Otherwise, the position of the peaks should be the opposite.

Time Allocation

In many, if not most, traditional nonmarket societies, food and other important commodities are produced and shared through the combined efforts of members of more than one nuclear family. Frequently, these nuclear families are linked through bonds of kinship. Among the Machiguenga and Piro, residential clusters are generally composed of an older couple (grandparents), their adult married children with sons—and daughters-in-law, and grandchildren (with some deviations owing to demographic variation). Most food in these residential clusters is eaten in communal meals. To simplify matters, we can model each three-generational "super-household" as a "dynasty" whose goal is to maximize lineage fitness. This initial approximation ignores sexual reproduction and conflicts of interest between family members, but it facilitates the generation of some qualitative predictions. As above, we can define fitness (thought of as the growth rate of the lineage), as

$$W = w(Z_{1,1}, Z_{1,2}, Z_{1,T}, \ldots Z_{n,T}) \qquad [9]$$

where $Z_{k,t}$ is the amount of the k^{th} commodity produced at time t, where T is some distant terminal date. Some of the important commodities in traditional societies are cooked meat, garden products, child safety, gains in knowledge and skill, social influence, and mate attraction. Each commodity, Z_t, is produced through the combination of component activities by each household member. For example, the production of garden products, such as manioc, involves forest clearing, burning, planting, weeding, harvesting, processing, and cooking. Thus the amount of k^{th} commodity produced, Z_k, will be a function of both the time that each household member allocates to each component activity and each individual's corresponding efficiency (return rate) at those activities,

$$Z_j = z_j(t_{1,1}R_{1,1}, \ldots t_{mn}R_{mn}) \qquad [10]$$

with t_{ij} being the time allocated by individual i to the j^{th} activity and R_{ij} being the corresponding return rate for each of the m members of the household over all n possible activities, and where activities are mutually exclusive and each individual allocates all available time. Thus, inserting equation 10 into equation 9, the dynamic household maximization problem is to maximize the rate of descendant production by the optimal allocation of activities by each household member at each point in time:

$$\begin{aligned} \text{Max}\,W = \; & w[Z_{11}(t_{111}R_{111} \ldots t_{nm1}R_{nm1}), Z_{1,2}(t_{112}R_{112} \ldots t_{nm2}R_{nm2}), \\ & Z_{1,T}(t_{11T}R_{11T} \ldots t_{nmT}R_{nmT}), Z_{n,T}(t_{11T}R_{11T} \ldots t_{nmT}R_{nmT})] \end{aligned} \qquad [11]$$

such that $\sum_{jt=1}^{n} t_j = t$ for all individuals. To complete the problem, it would be necessary to add demographic structure to the family dynasty by converting W into the proportional rate at which new individuals are produced and specifying a mortality function, with appropriate time discounting.

Even without fully analyzing this model, it is possible to generate some qualitative expectations. First, consider the one-period case with no concern for the future. In this situation, individuals should allocate time to tasks so as to maximize total output, w. The critical decisions will be the amount of each commodity to produce and the amount of time each individual should contribute to the component activities in its production. In general, since age-specific return rates are critical to production, we should find a rough correspondence between age profiles of time allocation and age profiles of return rates. However, efficiency also implies that individuals should specialize in tasks for which they have a comparative advantage; the rates of substitution among time inputs of different household members with varying return rates should be the most significant determinant of differential time allocation. Children can substitute most effectively for adults in low-skill, low-strength tasks because for these tasks the ratio of their return rates is closest to unity. Labor substitution among adults of different ages should reflect the relative contributions of strength and skill to tasks, with younger adults allocating more time to strength-intensive tasks and older adults allocating more time to skills-intensive tasks. Since return rates for all activities may eventually decrease with advancing age and senescence, we should expect older adults to spend most of their time in activities for which return rates decline more slowly. For example, if return rates for both hunting and agriculture decline with age, we would expect younger men to hunt more and older men to do more agriculture, if the physical rigors of hunting lead to more rapid declines with age. This may be true even if younger men achieve higher returns from agriculture than from hunting. In general, therefore, we should expect time allocation to change with age in much the same way that return rates change with age, with deviations resulting from rates of substitution among family members.

Infant care is an additional factor that should influence age profiles of time allocation (van den Berghe 1979). Infants require both frequent nursing and protection. Home is also a much safer environment for young babies than the forest. Moreover, infant care and breast-feeding do not strictly conform to the assumption of mutual exclusivity of activities. They can be combined easily with some activities, such as food processing and cooking, but not others, such as fishing or intensive garden labor (Hurtado et al. 1985). Since it is the mothers of babies who have milk to offer, older women cannot substitute for younger women in long bouts of childcare. Thus, older women may substitute for younger women in tasks that are incompatible with childcare and are performed away from home, whereas younger women may substitute for older women in home-bound activities. Such considerations should also generate deviations from a correspondence of age profiles of time allocation and return rates.

Next, consider the multi-period model. Two important new problems are introduced. The first problem concerns the impacts of time allocation on return rates during one time period to activities in subsequent time periods owing to the effects of learning and practice. Skills-intensive activities that yield high return rates by proficient workers most likely require a "learning period" in which immediate returns are low. Thus, the decision to allocate time to an activity at age a can be motivated not by immediate return rates, but by those expected at age $a + k$, discounted by the probability of reaching that age. For example, Machiguenga and Piro boys spend significant time hunting tiny lizards with bow and arrow. Although those lizards add little to household meat consumption, boys learn how to sneak up on animals without spooking them and improve their marksmanship, both of which presumably serve to increase return rates for hunting larger animals in the future. We should expect deviations in time allocation from single-period efficiency toward activities that provide learning opportunities for skills-intensive tasks (see

Bock 1995, 2002a, 2002b, for a similar argument and supporting data from villagers in rural Botswana).

In general, the costs of learning are lowest and the benefits are greatest at young ages owing to lower opportunity costs (since children are not very efficient at production) and to the additional years over which those returns will be realized (Becker 1991). Nevertheless, it may also be the case that returns to learning change nonmonotonically with age (see Bock and Johnson 2004 for a related discussion). For example, young children may learn little from treks into the forest in search of game, prior to having gained certain kinds of knowledge about prey behavior. Adolescents might learn more from such experiences. The general prediction is that individuals should engage in activities that provide opportunities to learn in such a manner that the marginal cost to current production is equal to the time-discounted expected future increases in production over the life course (cf. Becker 1991).

The second problem concerns the physiological costs and risks associated with given activities. Young children are probably at greatest risk of injury and even predation when engaging in productivity activities away from home. Most parents admonish children to stay close to home, presumably because they would risk injury or death. The physiological costs of intensive exertion and exposure to tropical heat are likely greater for old people than for young adults. Again, such considerations should produce deviations from single-period efficiency, given differential costs of work for future survival and productivity.

To summarize, the expected time allocated to a productive task (j) by an individual (i) can be modeled as a function of R_{ij}, and a suite of other factors (Y): $T_{ij} = g(R_{ij}, Y)$. The other factors can be grouped into three categories. The first group consists of variables relevant to household composition, such as the ratio of the number of consumers to producers (or dependency ratio), residential cluster (which captures effects of local food sharing and garden labor exchange), and the age-specific return rates of other household members (a proxy for availability of substitutable labor). A second is a set of age-related factors, such as nursing status, benefits to learning, and the risks and costs associated with work. The third includes factors associated with local ecology, such as the nature of production, rates of return to learning, and environmental hazards.

The grandmother hypothesis and the embodied capital models make different predictions about age profiles of time allocation, particularly with respect to the impacts of learning on both return rates and activity budgets. The grandmother hypothesis predicts that strength should be the major determinant of return rates and time allocation over the life course, particularly among women. The embodied capital model includes both strength and skill as arguments in the production function. This implies that age profiles of strength and skill will have differential impacts on return rates for different activities and that opportunities for learning will affect time allocation. In addition, the two theories, as they have previously been formulated, make different predictions about male time allocation and the role of meat acquisition. The grandmother hypothesis predicts that male behavior will be motivated by mating effort, whereas the embodied capital model predicts that male time allocation will be largely motivated by parental effort, with a division of labor among men and women that maximizes their joint fitness. The grandmother hypothesis views meat acquisition as display, whereas the embodied capital model views meat acquisition as a nutritional input that complements gathered and garden foods, in the service of supporting reproduction and children's growth and development. Testing these expectations motivates the empirical analysis to follow.

STUDY POPULATIONS

Both study villages are inhabited by native South Americans (Kaplan 1994). At the time of data collection the Yomiwato community consisted of 105 Machiguenga and was located in southeastern Peru on a small river in an area protected by the Peruvian government as a national park. Because of park policy, no economic development is allowed and its native inhabitants participate in a highly traditional economy with almost no access to money or wage labor. Their subsistence pattern during the study was based on swidden horticulture, bow-and-arrow hunting, fishing, and gathering (see Johnson 2003 for a thorough ethnography). The data were collected by K. Kopischke and Hillard Kaplan from September 1988 to May 1989.

The second community, Diamante, consisted of about 200 individuals of mixed, but mostly Piro, ancestry in southeastern Peru at the base of the Andes. The Piro economy was less traditional than that of the Machiguenga, having been exposed to the national economy for several generations. They practiced a mixed economy of horticulture (primarily manioc and plantains), shotgun hunting, fishing, gathering, and some wage labor. About 7–10% of total food consumed was purchased (about equal to the amount sold). The behavioral data were collected by M. Alvard and T. Phillips, under Kaplan's supervision, from August 1988 to June 1989. The same methods were employed in both study communities (see Alvard 1993 and Gow 2001 for background on the Piro).

METHODS

Data Collection

Production. The Machiguenga and Piro were both sampled using the same research design. Each community was subdivided into extended family residential clusters, which were physically separated from each other by a several minute walk. Clusters were equally sampled throughout the day in three four-hour sampling frames (morning, midday, afternoon). Focal follows on individuals were also conducted to estimate production outside the community. For the within-community sampling, identity of acquirers was recorded, along with weights of all foods acquired. Identifying the acquirer for garden production was difficult because most of the forest clearing, planting, and weeding tasks were performed by a single man, with some assistance from other men and the man's wife. However, harvesting for immediate consumption occurred every few days. Therefore, 50% of the garden calories acquired were assigned to the harvester and 50% to the person who performed most other garden tasks (i.e. burning, clearing, weeding, planting). This procedure was based on our finding that on average, 53% of time allocation to garden labor was spent harvesting.[5]

Large game acquisition and barbasco (poison) fishing were also sampled differently since both activities are relatively rare events and random sampling within households would yield large sampling error. Therefore, large game and barbasco fishing acquisition data were recorded for most individuals on all days in both communities.

In total, the Machiguenga sample represents 1,296 sample days of data on 87 individuals, and the Piro sample, 1,307 sample days on 139 individuals.

Time Allocation. The behavior of each individual within each household cluster was recorded every half hour within each four-hour sample block. Behaviors were either observed directly or recorded based on reports of others while individuals were away from camp. These reports were later verified by questioning the individuals upon their return. When individuals were observed performing more than one activity simultaneously, the activities were given equal weight such that their sum was equivalent to one observation. The mean number of observations per individual was 88 for the Machiguenga, 141 for the Piro.

Data Analysis

The recorded behaviors were organized into specific activity codes, which were then aggregated into several sets of more general activity categories. These general categories are foraging, gardening, schooling, childcare, food processing, employment, other work, and non-work. To calculate the average number of minutes per day individual i spends in activity x, we multiply the proportion of all observations for individual i spent in activity x by 12 hours/day and 60 minutes/hour. The total observations for this paper do not include time spent away from camp on overnight foraging trips or in wage labor. For each individual, we calculate the average number of minutes spent in all relevant activities.

We also construct four macro-categories defined in terms of strength and skill: low strength/low skill, low strength/high skill, high strength/low skill, and high strength/high skill. Table 1 lists the specific activities placed into these macro-categories. Activities were chosen that easily fit into our simplistic, binary partitioning of strength and skill.

Nonlinear Estimation

All curve fitting of return rate and time allocation data across the lifespan was done using nonlinear least squares estimation. We tested four different nonlinear

Table 1. Classification of Activities into Strength and Skill Categories

Low strength and skill	*Low strength, high skill*	*High strength, low skill*	*High strength and skill*
Household chores (HCH)	Household chores (HCH)		Community chores (CCH)
cleaning inside house (GCL)	clearing outside house (GCR)		
get water (GWT)			
Food processing (FCP)	Food processing (FCP)	Food processing (FCP)	Food processing (FCP)
chewing (FCH)	butcher/pluck (FCH)	pounding (FPO)	mashing (FMA)
shelling (FSH)	cutting (FCT)	carry resource (GCB)	get firewood (GFW)
straining (FST)	drying (FDR)		
serving (FSV)	peeling (FPL)		
Garden activities (GAC)	Garden activities (GAC)		Garden activities (GAC)
weeding (LGWD)	planting (LGPL)		clearing (LGCR)
			burning (LGBR)
			harvesting (RVG)
Fishing (FIS)			Fishing (FIS)
hook, line (RFK)			bow fishing (RFB)
barbasco (RFP)			net fishing (RFN)
			dig barbasco (LDGP)
Collecting (COL)			Hunting (HUN)
	Manufacturing		
	foraging equipment (MFE)		
	fishing items (MFS)		
	canoes, paddles (MOT)		
	household items (MHO)		
	Repair		Repair
	knife		transport vehicles (RTR)
	Repair/manufacture clothing		
	Repair/manufacture tools		

functions and chose the best fit to the data. The tested functions met several criteria. First, we only chose functions that exhibit close-to-linear behavior. This means that the estimators come close to being unbiased, normally distributed, with minimum variance, even with small sample sizes (Ratkowsky 1990). Second, all functions are capable of having peaks and inflection points for both the ascent and descent portions of the curves. Third, they are all functions of the single variable, age. Regressions were performed using the PROC NLIN in SAS, which employs the Gauss-Newton algorithm for estimating regression coefficients.

The nonlinear model that was used in this analysis was

$$Y_i = A \times \text{age}_i^{\,b} e^{c \times \text{age}} \qquad \text{Model 1}$$

where Y_i is either the average minutes per day individual i spends in activity j or number of calories produced per day or per hour, and age_i is the age of individual i.[6] Note that this model is structurally identical to the one derived using the Cobb-Douglas production function. The fact that this independent approach led to the same nonlinear model gives us additional confidence that our model provides the most efficient curvilinear fits to our data.

RESULTS

Table 2 reports the average minutes per day spent in various productive and nonproductive activities for male and female Machiguenga and Piro. The greatest differences between groups appear to be in hunting and schooling. In the analyses to follow, group differences are controlled with a dummy variable, but for the purposes of illustrating the age profiles, the illustrations do not disaggregate the data by village. Although standard goodness-of-fit measures are not straightforward for nonlinear models (Ratkowsky 1990), we report in Tables 3 and 4 the R^2 and p-values associated with the F-test for each of the nonlinear regression analyses reported below.

Rate of Productivity in Primary Subsistence Activities

Table 3 presents the results of the nonlinear estimation procedure for males and females. It shows the parameter estimates and significance levels for the intercept (A), and for the rise and decrease in return rates and time as they are jointly determined by m and n. The final column of the table displays the ages at which return rates or time peaks during the life course. The first and second parts of Table 3, respectively, examine return rates and time for the four main subsistence activities: hunting, collecting, fishing, and gardening. The third part examines activities grouped in terms of skill and strength requirements: low strength/low skill (0,0); low strength/high skill (0,1); high strength/low skill (1,0); and high strength/high skill (1,1). The fourth part treats other uses of time, (for which return rates are more difficult, if not

Table 2. Time Allocation (average minutes/day) to Various Activities by Sex and Group

	MALES			FEMALES		
Activity	*Machiguenga* (*n* = 42)	*Piro* (*n* = 75)	*Total* (*n* = 117)	*Machiguenga* (*n* = 45)	*Piro* (*n* = 64)	*Total* (*n* = 109)
Hunting	48.8	19.6	30.1	0.4	4.2	2.6
s.e.	(8.9)	(3.7)	(4.2)	(0.1)	(1.3)	(0.8)
Collecting	18.8	12.7	14.9	24.9	11.9	17.2
s.e.	(3.1)	(2.1)	(1.8)	(3.7)	(2.5)	(2.2)
Fishing	22.4	43.2	35.8	12.0	14.6	13.5
s.e.	(3.7)	(6.2)	(4.3)	(2.1)	(2.9)	(1.9)
Gardening	16.4	25.6	22.3	15.8	27.0	22.4
s.e.	(3.8)	(4.1)	(3.0)	(3.0)	(4.7)	(3.1)
Food Processing	11.1	10.4	10.7	54.7	41.0	46.8
s.e.	(1.7)	(2.7)	(1.8)	(6.8)	(5.8)	(4.5)
Child Care	6.7	2.8	4.2	38.3	38.8	38.6
s.e.	(2.0)	(1.1)	(1.0)	(8.2)	(6.7)	(5.2)
School	33.3	68.0	55.6	17.0	51.8	37.2
s.e.	(6.6)	(12.3)	(8.3)	(4.2)	(10.8)	(6.7)
Other Work	46.0	165.6	122.7	81.7	253.6	181.3
s.e.	(6.4)	(21.6)	(15.0)	(10.4)	(27.1)	(18.3)
Leisure	388.8	408.6	401.6	347.4	386.0	370.1
s.e.	(16.0)	(11.7)	(9.7)	(14.5)	(14.5)	(10.5)

impossible, to calculate). Figures 3 to 14 display the predicted values from this procedure, as a function of age and sex.

Figures 3a and 3b display return rates of the three foraging activities for men and women, respectively; Figure 3c displays the much-higher return rates for agriculture separately. The return rates are estimated by dividing daily caloric production for each activity by hours per day spent at each activity using the predicted values derived from the parameter estimates displayed in Tables 3 and 4. In order to standardize rates across activities, return rates at each age were also divided by the highest predicted return rate for that activity, so the age with the highest return rate has a score of one and all others are scored as a proportion of that return rate. Those results are displayed in Figures 4a and 4b for males and females, respectively.

Men achieve their peak return rates earliest for collecting (age 28), followed by fishing (age 40) and then by hunting (age 45) (see Table 3 and Figures 3a and 4a). Collecting requires relatively low strength and skill, fishing is not strength-intensive but is moderately skill-intensive, and hunting is both strength—and skill-intensive. The peaks in fishing and hunting return rates occur much later than the age of peak strength, which in most samples occurs in the early to mid twenties (Walker

Table 3. Regression Diagnostics and Parameter Estimates for Nonlinear Model of Time and Caloric Return Rates, Shown for (*a*) Males and (*b*) Females. The three variables *m*, *n* and *A* are estimated parameters from the nonlinear equation $Y = A \times \text{age}^m e^{n \times \text{age}}$, where *Y* is either return rates (daily caloric productivity divided by daily time expenditure in minutes) or time (average minutes per day).

	Diagnostics		*A*		*m*		*n*		Age at Peak
A. Males	R^2	*p*	estimate	*p*	estimate	*p*	estimate	*p*	
RETURN RATES									
Hunting^g	0.22	***	4.80E-05		6.837	*	-0.197	*	45
Collecting	0.15	***	0.036		4.313	*	-0.151	†	28
Fishing	0.32	***	0.002		4.747	**	-0.110	*	40
Gardening	0.71	***	0.026		4.231	***	-0.076	**	68+
TIME									
Hunting	0.33	***	0.049		3.157	**	-0.116	**	27
Collecting	0.14	***	3.161		0.821	*	-0.027		30
Fishing	0.33	***	2.533		1.057	**	-0.017		62
Gardening	0.51	***	0.013		2.901	**	-0.059	*	49
low (str), low (skill)	0.09	***	34.169	***	0.090		0.005		68+
low, high	0.45	***	0.464		1.616	***	-0.028	**	57
high, low	0.08	***	0.407		0.794		-0.020		39
high, high	0.65	***	0.372	†	2.392	***	-0.065	***	37
food processing	0.11	***	0.004		3.576	*	-0.118	*	30
child care	0.14	***	1.52E-26		28.133		-1.147		25
manufacture/repair	0.22	***	1.352		0.752		0.004		68+

Table Continued

et al. 2002). The very high return rates for gathering represent the effects of self-selection, in that men only gather rarely, when returns are expected to be particularly high (e.g., the fruiting of wild-growing avocado trees or the harvesting of large larvae patches from previously felled palms). The early peak in collecting return rates is probably due to both its relatively unskilled nature and the fact that high returns are achieved far from the settlement, in combination with hunting. Hunting and fishing tend to occur during the wet and dry seasons, respectively; during the former, fish are difficult to catch and animals are fat, and during the latter, fish are easier to find and many animals are considered hardly worth the effort because they are parasitized and skinny because of the lack of fruit.

Young and middle-aged women show a significant peak in collecting productivity (Figures 3b, 4b). Women achieve very low returns from hunting, probably owing to their lack of practice (only a few actively hunt, and they do so rarely). Fishing

Table 3. Continued

	Diagnostics		*A*		*m*		*n*		Age at
A. Females	R^2	p	estimate	p	estimate	p	estimate	p	*Peak*
RETURN RATES									
Hunting	0.06	**	5.79E–22		21.758		–0.747		29
Collecting	0.25	***	0.006		4.530	*	–0.132	*	30
Fishing	0.21	***	1.730		1.357		–0.017		38
Gardening	0.55	***	4.270		2.504	***	–0.059	**	39
TIME									
Hunting	0.03	**	1.206		0.578		–0.018		32
Collecting	0.24	***	3.354		0.622	†	–0.003		57+
Fishing	0.25	***	2.979		0.561		0.004		57+
Gardening	0.27	***	1.236		1.243	*	–0.026		48
low (str), low (skill)[g]	0.34	***	14.929	†	0.695	**	–0.014		50
low, high	0.59	***	1.838		1.414	***	–0.025	*	57
high, low	0.14	***	1.022		0.807	†	–0.023		35
high, high	0.22	***	14.883	*	0.404	*	2.30E–05		60+
food processing	0.50	***	3.011		1.209	***	–0.003		45
child care	0.18	***	0.001		5.639	**	–0.247		23
manufacture/repair	0.30	***	0.004		3.528	*	–0.083	*	43

*** $p < 0.0001$, ** $p < 0.01$, * $p < 0.05$, † $p < 0.10$

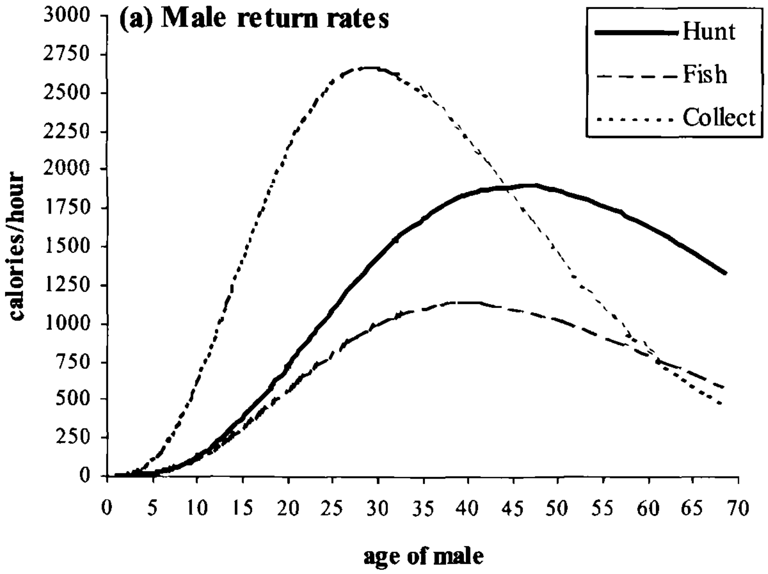
[g] significant difference (at 0.05) between Machiguenga and Piro

Note: Parameter estimates for return rates are derived from regressions of daily caloric productivity and time by first fitting these models to daily caloric production for each activity and time. The predicted values of caloric productivity per day were divided by predicted values of hours spent per day to derive predicted return rates, which were then fit to the model.

returns are lower than for men, and those returns remain relatively steady through adulthood with only a slight decrease at older ages.

The data on agricultural return rates ostensibly show that men are increasingly productive with age (Table 3 shows a peak at the oldest age). This is likely to be an artifact of the less direct method used for assessing agricultural productivity as well as sample bias. Recall that 50% of each calorie harvested was assigned to the harvester and 50% to the man who cleared and weeded the field. Older men's fields tended to be larger, but much of their clearance time was not recorded because it occurred during the early dry season when river travel to Yomiwato was impossible. Moreover, it is also possible that older men received more help from younger kinsmen in field clearance, since much of the surplus went directly to their children and grandchildren. Data on rates of tree felling and garden clearance would be particu-

Figure 3. Caloric return rates by age and sex for four primary subsistence activities: (*a*) and (*b*) show caloric return rates by age for males and females, respectively, for hunting, fishing, and collecting activities. (*c*) shows the caloric return rates by age for gardening for both males and females.



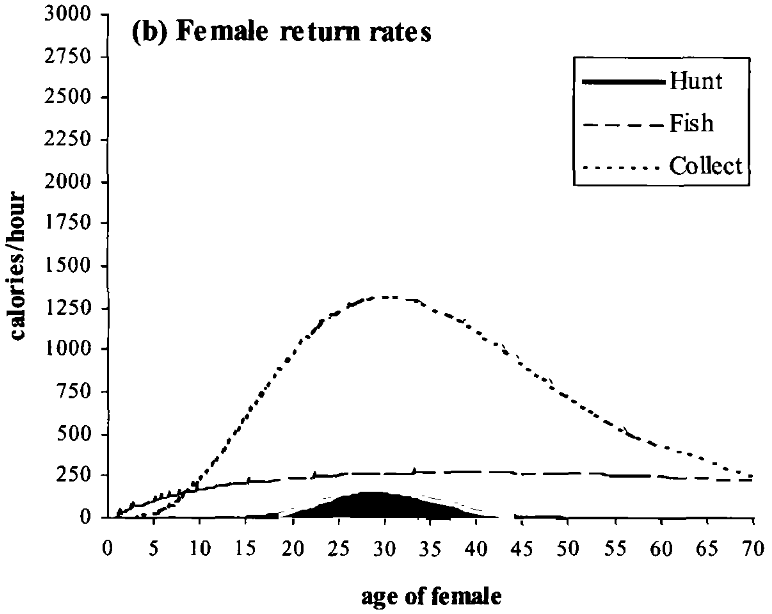
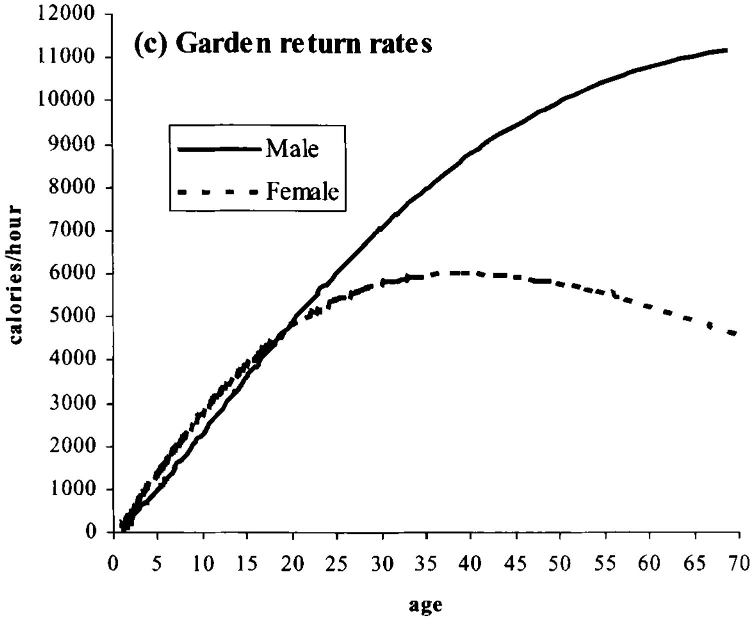


Figure 3. continued



larly helpful in clarifying this age pattern. Return rates for women show that harvesting productivity peaks about age 39 and only drops off slowly. The estimates of women's return rates do not suffer from the same problems of bias as men's, because almost all of their garden labor is harvesting.

Time Allocation to Primary Subsistence Activities

Time allocation to primary subsistence activities is shown in Figures 5a and 5b for males and females, respectively. As mentioned previously, men's time allocation to collecting is rather insignificant and remains relatively steady throughout adulthood. Hunting shows a sharp rise in late adolescence, peaking at age 27, and then dropping off rather rapidly, with 50-year-olds hunting less than half the time of 25-year-olds. These decreases probably reflect the strength—and endurance—intensive nature of hunting. Fishing, in contrast, increases monotonically throughout the life course, consistent with the fact that it requires relatively high skill levels but is less difficult to sustain. Garden work peaks at about age 49 and then drops off (this decrease in time allocation to gardening while amount harvested from garden remains steady or increases is the cause of the monotonically increasing return rate, of which we are suspicious). The women's data show that hunting is relatively rare throughout adulthood, whereas fishing and collecting rise through adulthood. As with men, agricultural effort peaks in the late forties, and then drops off slowly.

Figures 6 and 7 examine return rates and time allocation jointly for selected

Figure 4. Standardized caloric return rates by age for four primary subsistence activities for (*a*) males and (*b*) females.

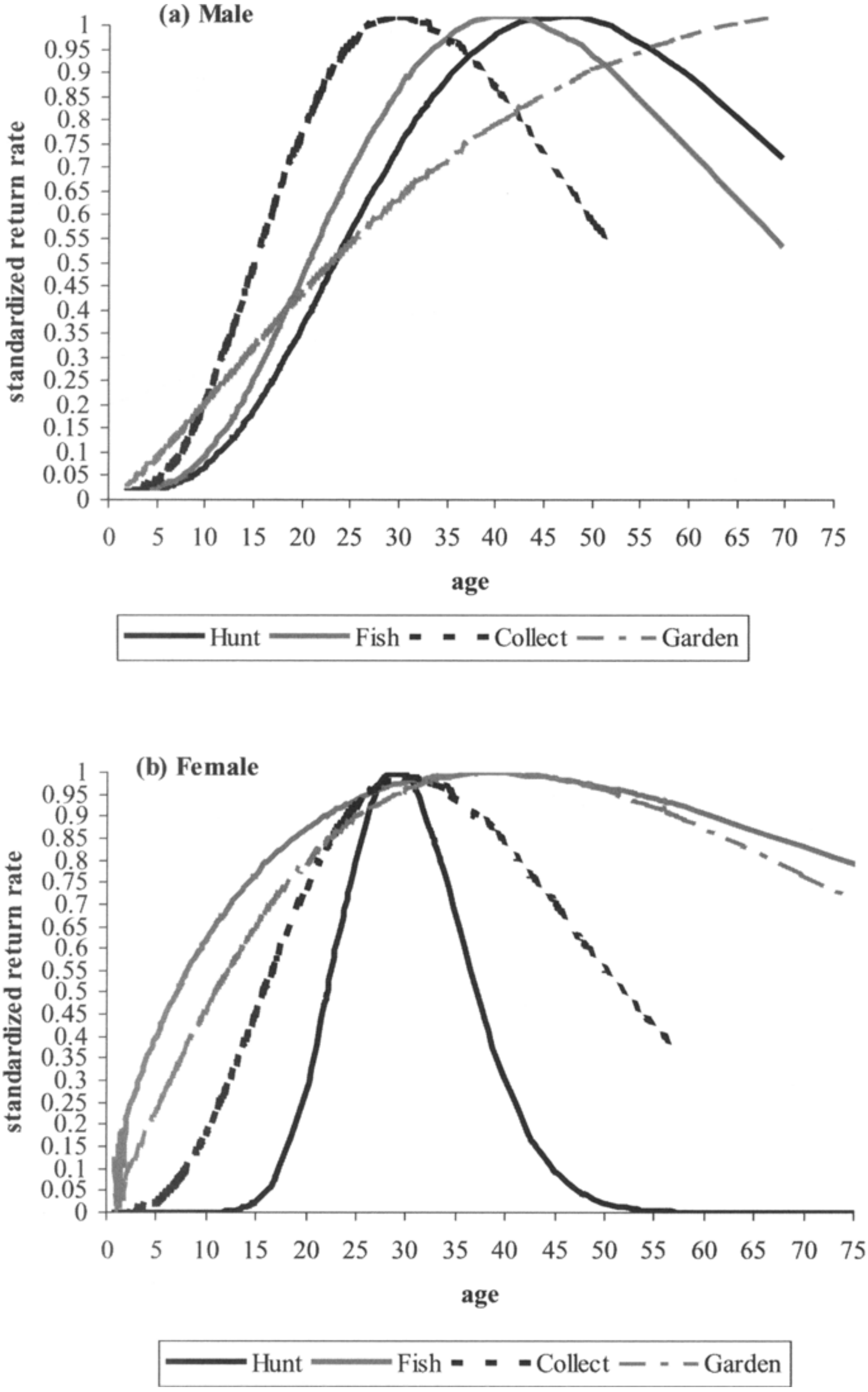
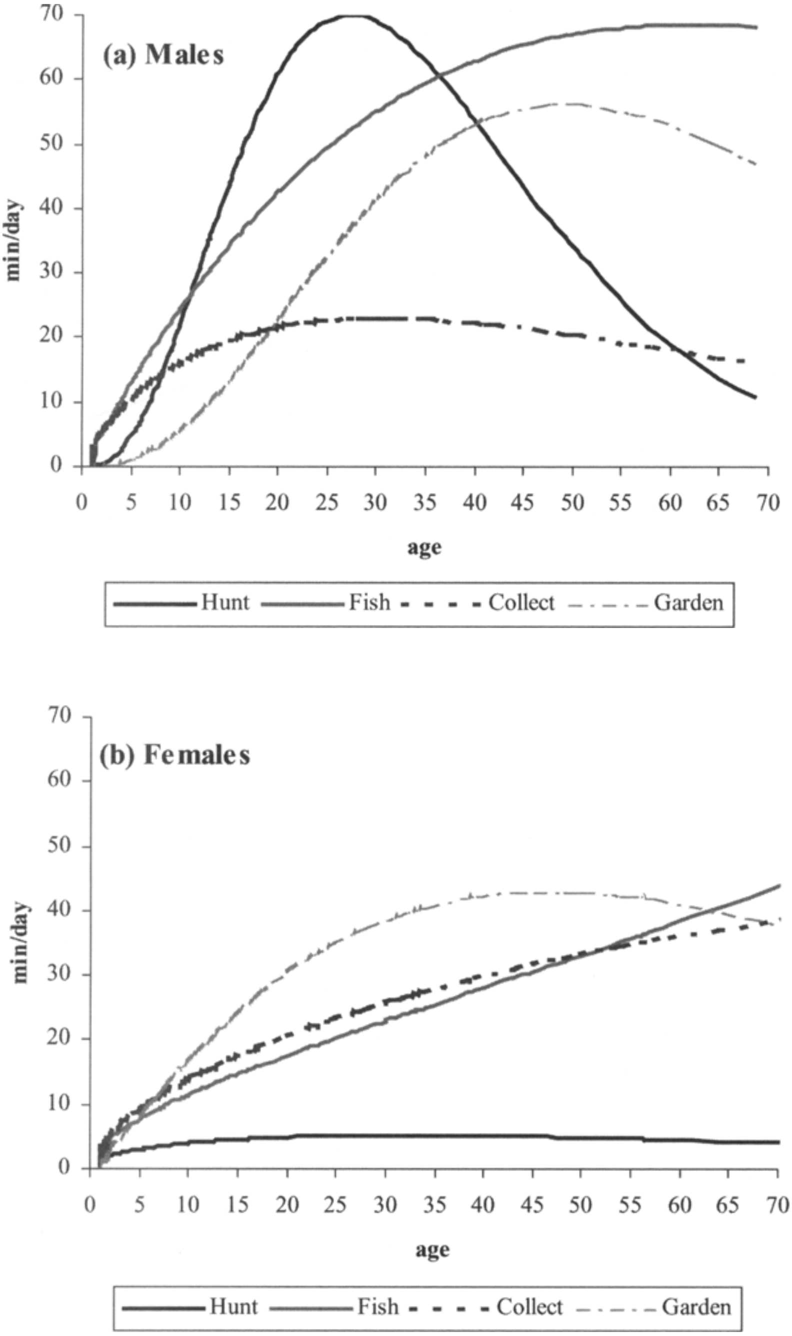


Figure 5. Average time (minutes per day) spent in four primary subsistence activities by age of individual, for (*a*) males and (*b*) females.



activities, for men and women, respectively. Figure 4a showed that for men, time allocation to hunting peaks well before return rates. This seems to be indicative of the long learning period involved in hunting, and the costs of high endurance later in life. Children's time allocation to fishing also seems to reflect investment in learning, with time increasing faster than return rates (Figure 6b). However, unlike hunting, fishing return rates peak at age 40, while time allocation continues to increase until the early sixties. Thus, men shift their time allocation away from the more endurance-intensive hunting to fishing as they age. In contrast, Figure 7 shows that women's return rates increase much more quickly toward their peak than does their time allocation, which increases throughout adulthood and middle age. This is indicative of factors other than return rates in determining women's time allocation, as will become clear below. Figure 7d shows that women's agricultural return rates and time allocation profiles have very similar shapes, but again time remains high while return rates begin to decrease in old age.

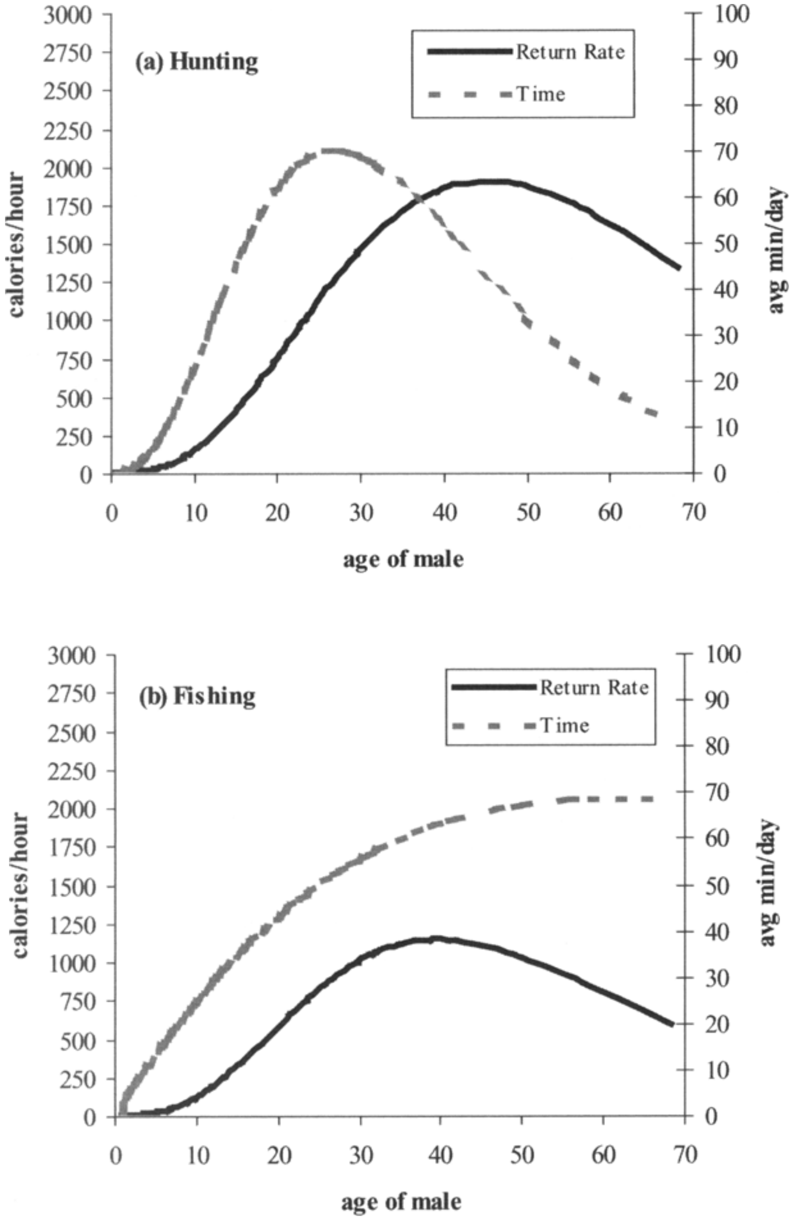
Figure 8 shows time allocation to other important forms of work for men and women: food processing, manufacture and repair of technology, childcare, and other work. Other work includes such activities as cleaning, washing clothes, building houses, getting water, and community labor. As is evident in Figure 8a, men spend very little time in childcare and food processing. Time in childcare peaks at about age 25, with a mean of about 10 minutes per day, and is mostly restricted to the period from late teens to age 30. Food processing time peaks around age 30 at just over 20 minutes per day. Manufacture and repair of tools is highly skilled but not strength-intensive. It is therefore not surprising that time spent in those activities increases through life, peaking for men at 40 minutes per day in their sixties. Women, in contrast, spend a great deal more time in childcare and processing food. For example, 15-year-old girls spend about 60 minutes caring for children (about six times as much as men at their peak), even before they have reproduced. Time spent in childcare peaks in the mid twenties at about 100 minutes per day. The age pattern is highly peaked. Women spend as much as 90 minutes per day processing food. One of the major processing activities is preparing manioc beer, which constitutes up to 30% of the calories ingested! Women also spend a great deal of time in manufacture and repair, especially hand-spinning cotton and weaving clothes. These activities peak in the mid forties.

Strength and Skill: Time Allocation by Activity Requirements

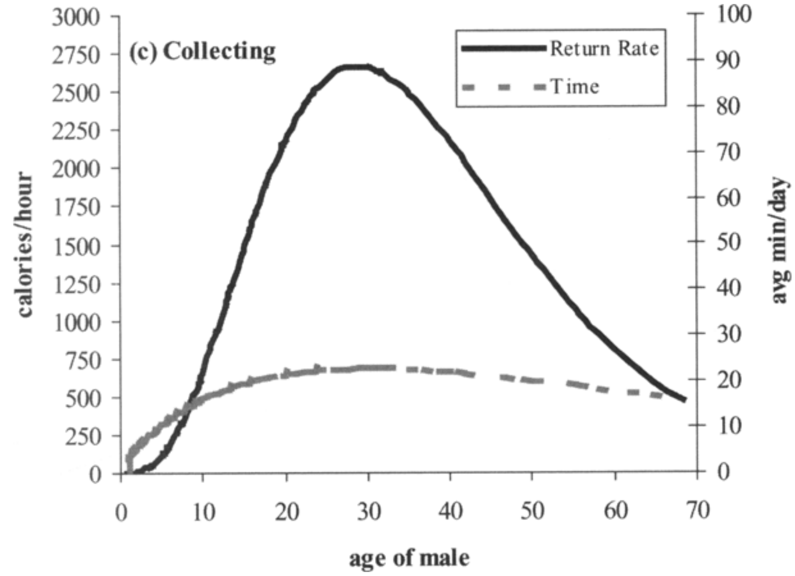
We now take a more general empirical approach to examining the relationship between strength and skills requirements of activities and time allocation behavior. Figure 9 gives the nonlinear fit of time males and females spent engaging in activities within each of the four skills and strength categories given in Table 1.

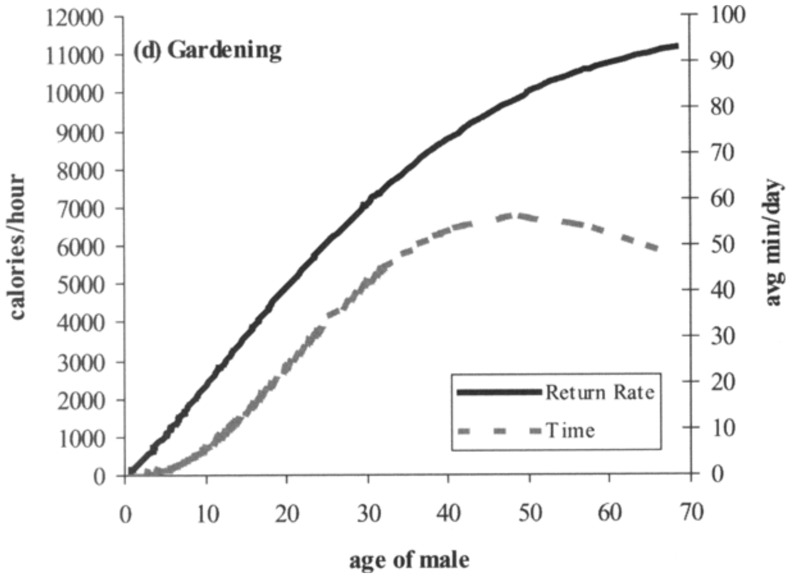
Time spent in low-strength/low-skill activities increases throughout the lifespan for both males and females, although there is little difference between child and adult levels. Figure 10 gives the standardized time allocation curves for males and

Figure 6. Male caloric return rates and time allocation for (*a*) hunting, (*b*) fishing, (*c*) collecting, and (*d*) gardening. Solid lines are return rates and broken lines are time allocation.



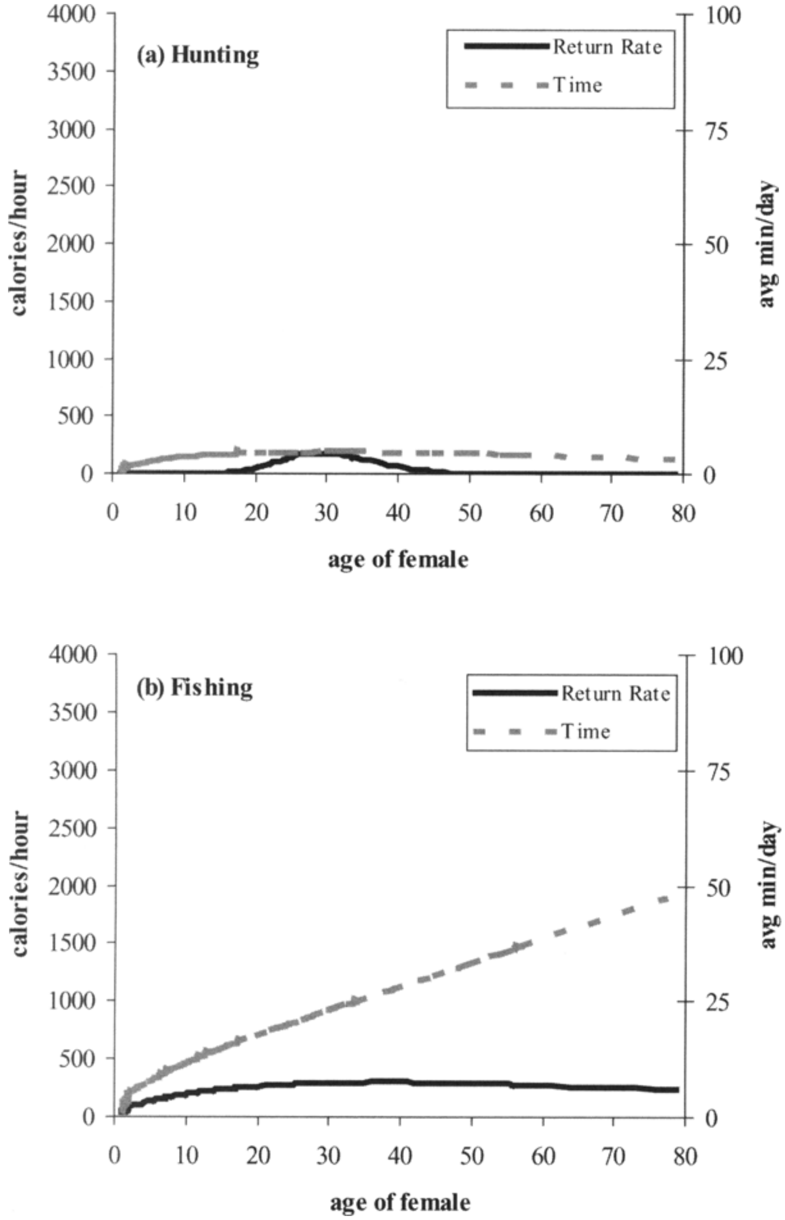
females. By age 10, males and females have reached roughly half of their adult body weight. Body weight is a good proxy for physical strength and is a more conservative proxy than body height. For low-skill activities, males have reached roughly 50–60% and females 60% of the adult maximum. Thus, time spent in these





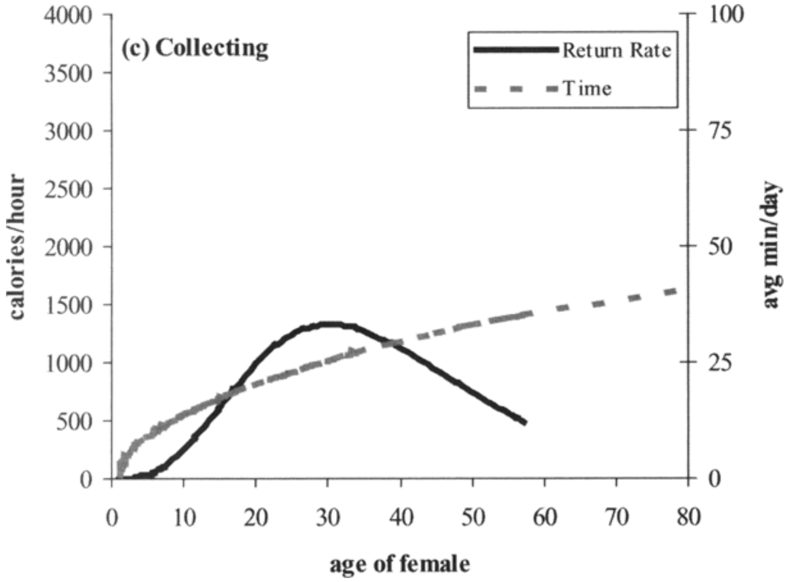
activities scales with body size. Conversely, for high-skill activities, a 10-year-old male has reached only 25% and a female 20–40% of the adult maximum. At age 20, when physical growth has mostly finished for males and has already finished for females, men's time allocation to high skill activities is still only 50–60% of the maximum, and women's is only 40–50%. However, a 20-year-old man's and woman's time allocation to low-skill activities is 60–80% and 70–90% of the maximum,

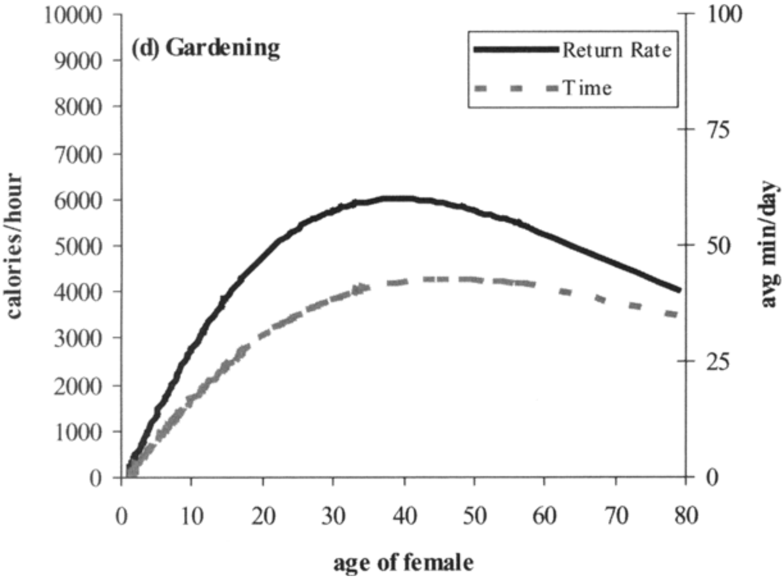
Figure 7. Female caloric return rates and time allocation for (*a*) hunting, (*b*) fishing, (*c*) collecting, and (*d*) gardening. Solid lines are return rates and broken lines are time allocation.



respectively. These data correspond closely to the age profiles of productivity discussed above.

As we might also expect if return rates directly influence time decisions, there is little or no decline from peak activity for males for low-strength activities, but there is a significant decline for high-strength activities (Figures 9a and 10a). For fe-





males, there is also no decline for low-strength activities, and we also find a decline for high-strength/low-skill activities. However, for high-strength/high-skill activities, women's time allocation increases over the lifespan. This difference between men and women could be because high-strength activities for men such as hunting may be more physically demanding and subject to more rapid deterioration than high-strength activities for women, such as mashing food (see Table 3). Thus, as strength declines, men appear to shift time allocation to high-skill activities with

Figure 8. Time spent in food processing, manufacturing and repair of household items and technology, childcare, and other work activities, such as house construction, cleaning house, washing and sewing clothes, and community labor, for (*a*) males and (*b*) females.

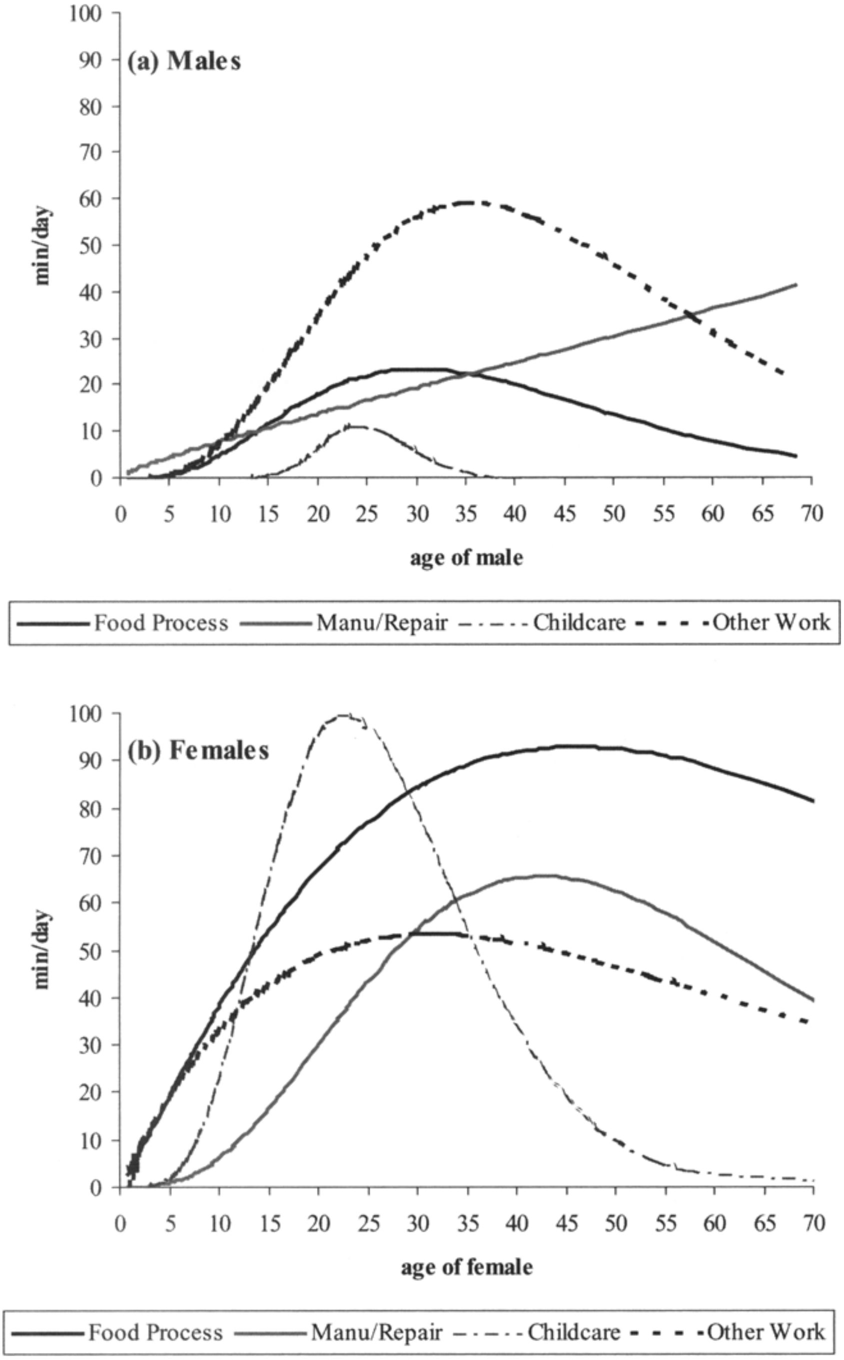
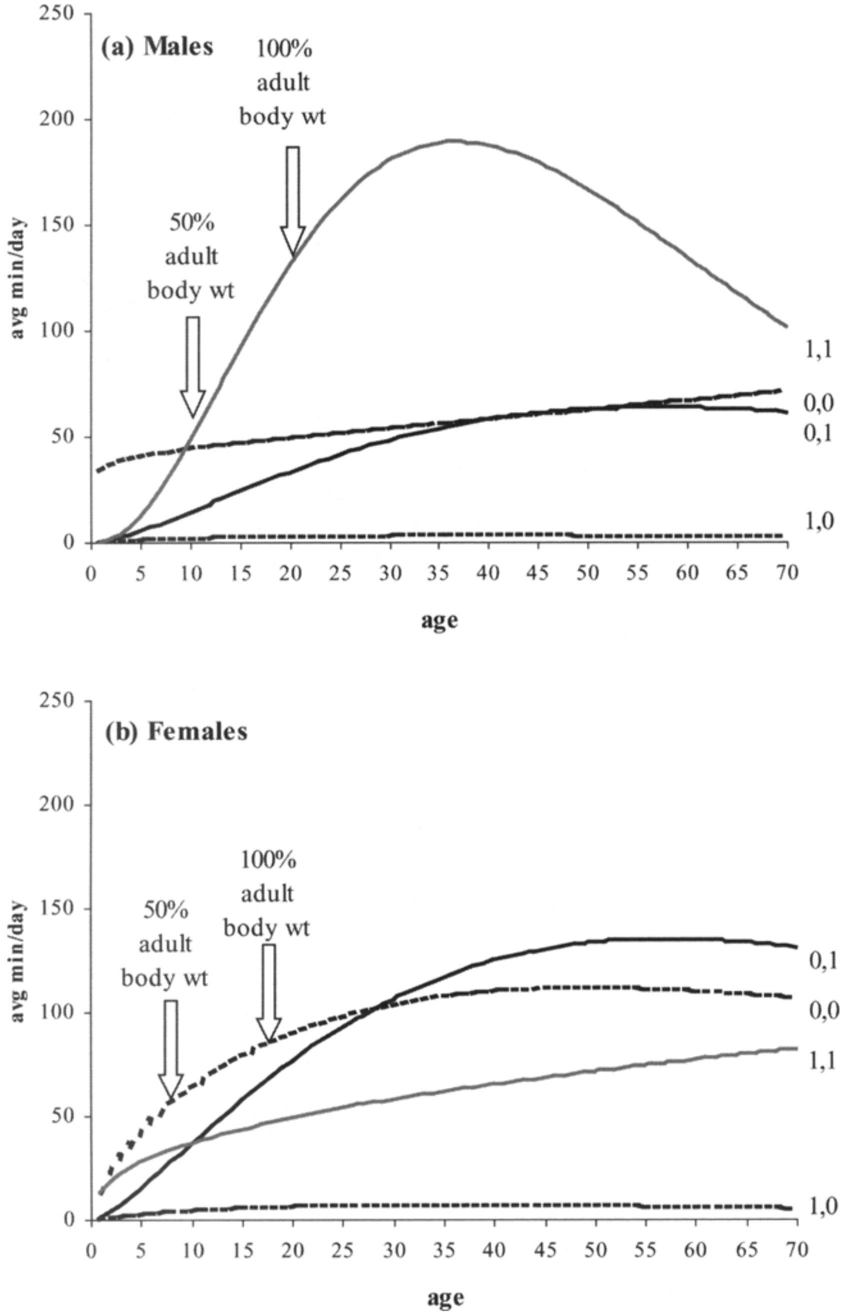


Figure 9. Time spent in four macro-categories of activities for (*a*) males and (*b*) females based on strength and skills requirements. 0,0 refers to low-strength/low-skill activities; 1,0 to high-strength/low-skill activities; 0,1 to low-strength/high-skill activities; and 1,1 to high-strength/high-skill activities. Activities in each macro-category are given in Table 1. Arrows indicate ages at which males and females have reached 50% and 100% adult body size.



low strength requirements (e.g., manufacture and repairing tools; see Figure 8a), while women do the same but can also more easily maintain high levels of high-strength activities.

Total Production: Calories and Time

Figure 11 shows the cumulative *daily* energy production for men and women. First, returns from hunting are plotted, fishing returns are then added, followed by collecting, and then gardening. Figure 11a shows that for men, most hunted calories are obtained during their thirties. Men obtain somewhat fewer calories from fishing, and production remains relatively steady until age 60. Collecting does not contribute many calories to the diet, and most of them are acquired by younger men, probably during hunting expeditions. Men's gardens produce the bulk of the calories they provide, especially as they age. Caloric production from all sources peaks in the men's late forties. Figure 12 normalizes the data by dividing age-specific production from each source by total production at that age. This shows the relative contribution of calories from different sources by men's age. From about ages 18 to 40, meat from hunting and fishing constitutes just under 30% of the diet, and it drops below 20% by age 50.

Figure 11b shows the cumulative daily caloric production for women. Calories from hunting are negligible, and calories from fishing are not much greater, increasing with age to about 10% of production late in life (Figure 12b). Collecting provides more calories, particularly in middle adulthood. By far the bulk of calories provided by women is derived from harvesting manioc and plantains from the garden. Total production by women peaks in the forties, but it is only about 4,900 calories per day, compared with men's peak at about 12,000 calories per day.

Figure 13 displays time allocation cumulatively for men and women. Men peak in work effort in their mid thirties, working about five hours per day (a 35 hr work week), whereas women work about an hour a day longer (a 42 hr work week). Men's allocation of time to work declines at a faster rate than women's, largely owing to the drop in high-endurance activities. In general, men begin their adult lives with a focus on hunting and then shift their effort to less demanding activities, such as fishing, gardening, and tool manufacture. Tool manufacture becomes an increasingly important aspect of men's contributions as they age.

DISCUSSION AND CONCLUSIONS

The age—and sex—profiles of return rates and time allocation among the Machiguenga and Piro reflect a life history in which both physical strength and skill are important to economic production and where individuals of different ages and sexes make very different contributions to household production and reproduction. Young children engage in very little work. In fact, as shown in Figure 11, they produce a very small percentage of the calories they consume before age 10. This

Figure 10. Standardized version of Figure 9, where times are normalized to maximal adult levels. Vertical lines indicate ages at which males and females have reached 50% and 100% adult body size.

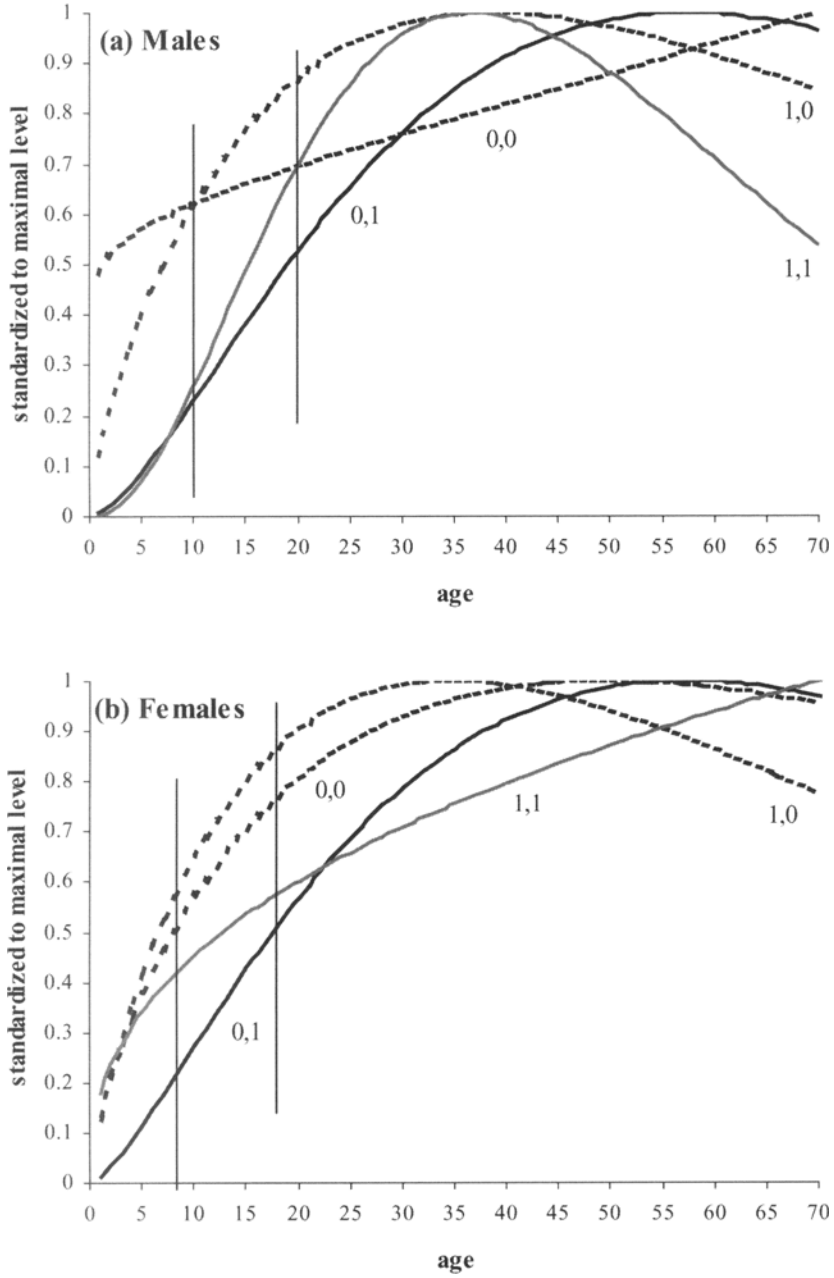


Figure 11. Total cumulative daily caloric production by age for (*a*) males and (*b*) females. Caloric production activities are stacked, starting with hunting, then adding fishing, collecting, and gardening calories.

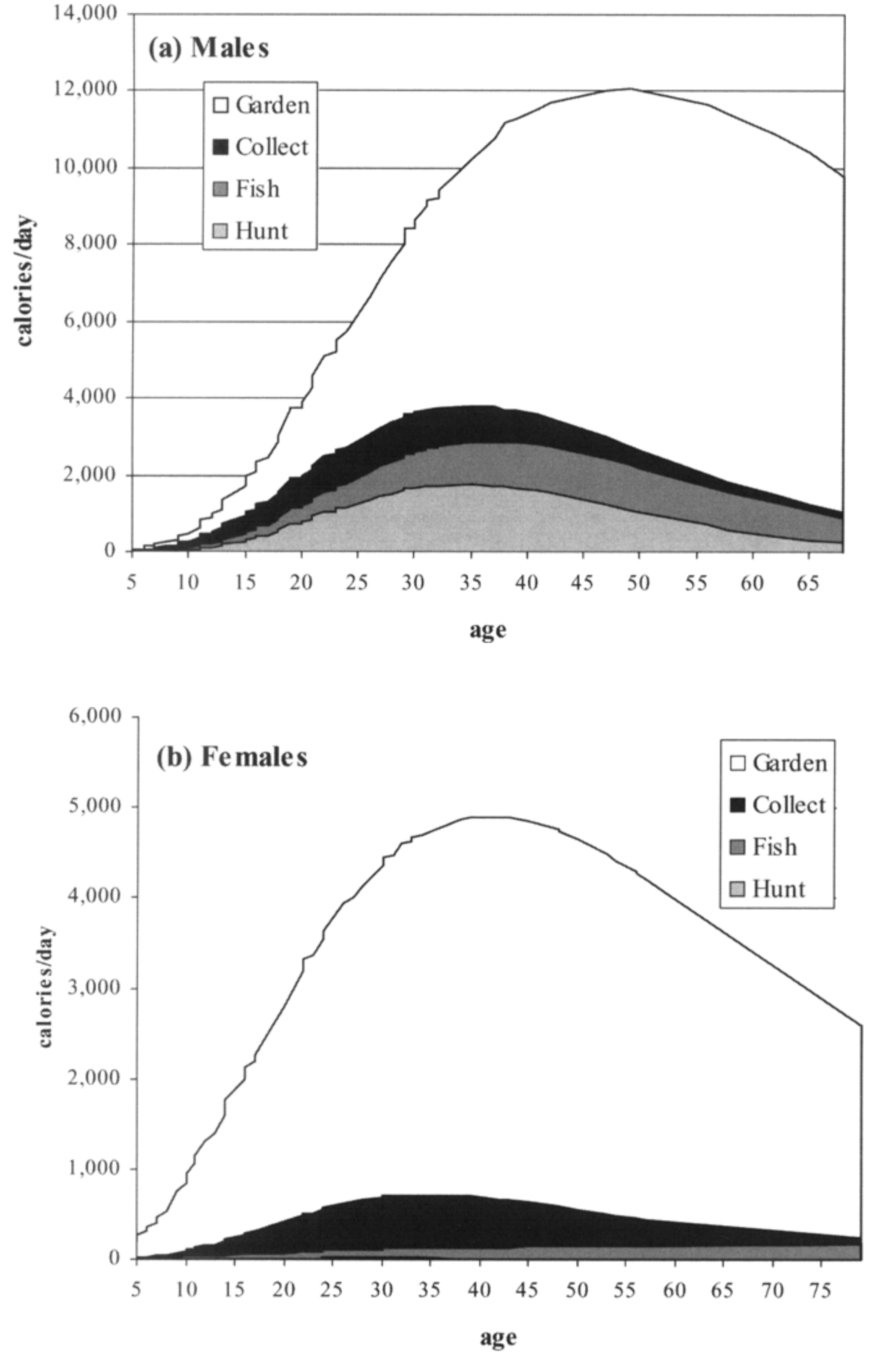


Figure 12. Age-standardized version of Figure 11. The *y*-axis measures the percentage of daily caloric production attributed to hunting, fishing, collecting, and gardening activities.

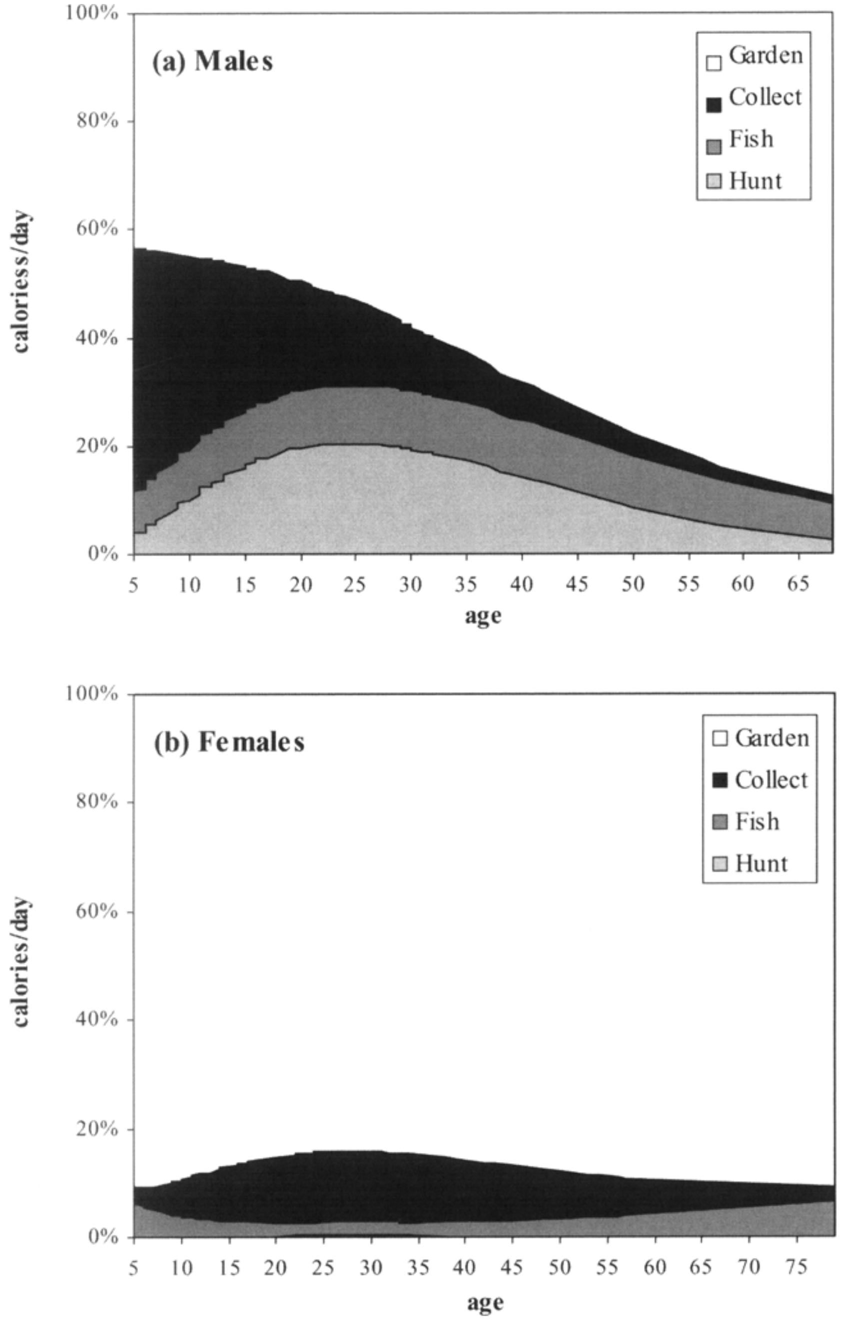


Figure 13. Total cumulative daily time allocation for work activities by age for (*a*) males and (*b*) females. Time spent in activities are cumulative, starting with hunting, then adding fishing, collecting, gardening, food processing, manufacturing and repair, childcare, and other work activities. The average work day is 5 hrs for men and 6 hrs for women at their peak.

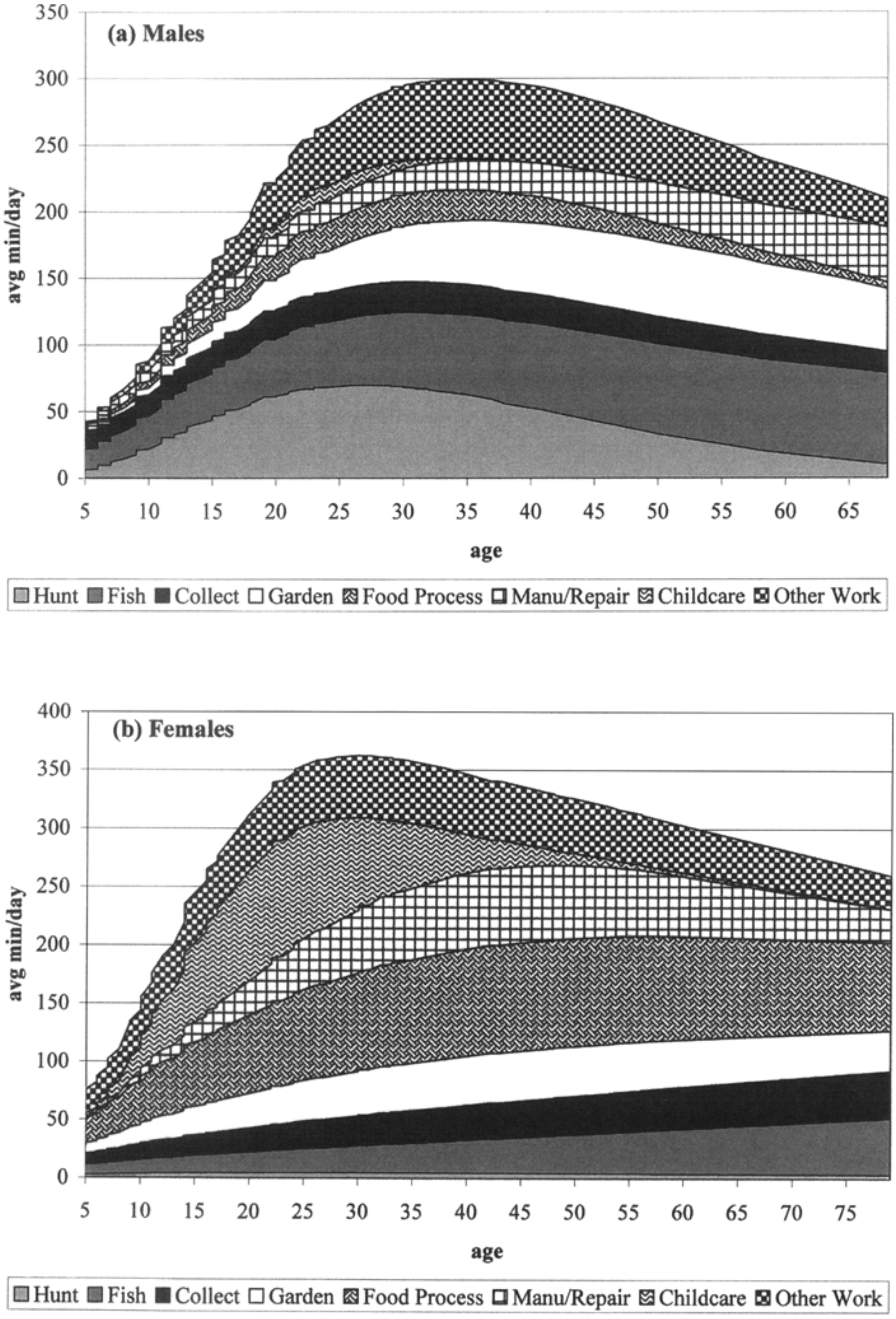
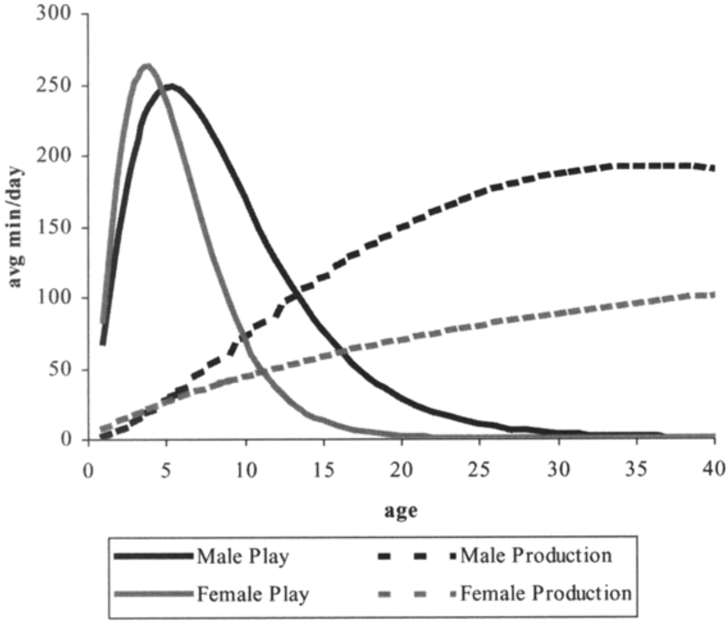


Figure 14. Total time males and females spend in play and all food-production activities, across the lifespan.



contrasts sharply with our closest primate relatives, both monkeys and apes, whose infants begin feeding themselves during late infancy while they are still nursing. This intensive provisioning appears to be part of a life history that specializes in high levels of infant and child survival, a long learning period, and high productivity in adulthood and middle age. Most of children's time is spent in play, which may be a safe way of learning skills (Bock and Johnson 2004). Figure 14 shows that time spent in play and productive labor negatively co-vary across the lifespan. Infants are kept safe and do very little; this is followed by a burst of play, which then drops off as productive labor increases. During childhood, productive labor is spent primarily in low-strength/low-skill tasks among both males and females.

The life histories of males and females diverge radically in adolescence and early adulthood. This divergence reflects male specialization in high-skill/high-strength tasks, and female specialization in combining childcare with productive labor in less-strength-intensive tasks. For males, meat acquisition is an important focus from late childhood through middle adulthood. Boys begin by spending more time fishing than hunting (the former being both less strength—and endurance-intensive as well as safer) and then as their strength increases during adolescence they begin to allocate increasing effort towards hunting. By their mid-twenties, they have reached peak strength and time allocated to hunting. The skill-intensive nature of hunting is reflected in the delay to peak return rates. Figure 6 shows that peak return rates from hunting occur about two decades after strength and time allocation peak. In fact, by the time men reach peak returns from hunting, they have already begun to shift much of their time allocation toward less strength—and endurance-intensive tasks, but still skills-based tasks such as agriculture and tool manufacture and repair. Greater investment in agriculture may reflect both the increased caloric demands of their growing families and the cumulative effects of several decades of hunting on their bodies.

The life history of females after childhood shows two distinct phases. The first phase appears to be focused on providing care to infants and children. Even before they begin to reproduce, girls spend an increasing proportion of their work effort in childcare (about 20% at age 15). This may reflect a learning phase before they are responsible for their own baby (Kramer 2002). Early adulthood is largely focused on childcare, and on tasks that are compatible with staying at home in a safe environment and on-demand breast-feeding, such as food processing and other household work. As women age, they spend an increasing proportion of their time in food production and manufacture. Given that time spent in childcare peaks in the early twenties, it would appear that as the number of a woman's dependent children increases, she compensates by increasing food-related work effort at the expense of childcare (Figures 7 and 8). It is also interesting that women spend an increasing proportion of time fishing and collecting as they age, even into old age; those activities require leaving home and compete most with childcare.

How do the alternative models of life history and time allocation through the life course fare in light of these data? The results are largely consistent with the embodied capital approach to time allocation over the life course, as developed by Bock (2002a, 2004b) and formalized here. The results show that time allocation over the life course reflects labor substitution among members of extended families. It is shaped by the effects of both skill and strength on performance in specific tasks, and by opportunities for learning. In this sense, the patterns of labor substitution among the Machiguenga and Piro are similar to those found by Bock for HamBukushu villagers in Botswana (2002a, 2004b) and by Kramer among Maya in Mexico (Kramer 2002). However, Machiguenga and Piro children require more years to become effective producers than do Mayan children, presumably because Mayan peasant farmers have more low-skill tasks in food production than the forager-horticulturalists in Peru (see Kramer and Boone 2002 and Lee, Kramer, and Kaplan 2002 for supporting analyses).

The results also suggest a refinement of Bock's (2004b) concept of punctuated development. In his view, development may proceed in a steplike fashion for many tasks that involve both strength and skill. This is because it will not pay to invest time in learning some tasks until the body is strong enough to perform them effectively. Thus, it may appear that it takes a long time to learn the task, when in fact the developmental process is characterized by a long growth process, followed by a spurt in learning. This may be true for some tasks, such as fishing with baskets, which require moderate levels of strength and skill. However, we expect that length of learning period and the rate at which return rates increase will depend on the degree to which cumulative learning affects task performance. Rates of return on labor peak at increasingly older ages, as the skill: intensiveness ratio of the activity increases; collecting return rates peak first, followed by fishing and then hunting. Moreover, peak return rates for fishing and hunting occur long after strength peaks. In addition, time allocation to these activities increases faster than do return rates, also indicating an investment phase through which rates increase as a result of learning-by-doing. The learning period can be quite long, with steady increases in return rates for a decade or two following peak strength acquisition and a period of heavy time investment in the activity. Tool manufacture, especially of highly technical items such as bows, arrows, and boats, may require many decades to learn well. As strength and endurance begin to wane, both men and women, but especially men, allocate more time to more-skill- but less-strength-intensive activities.

Although these results do not support the strength-only view favored by proponents of the grandmother hypothesis, two features of the results are consistent with the grandmother hypothesis. First, strength does appear to play a role in the patterning of activities, in terms of both return rates and time allocation, as they change with age. There is an increase in rates as children grow and a decrease as men and women age. Second, and most important, older women do work hard and provide surplus calories for younger women. For example, a 60-year-old woman produces more calories, about 4,000 per day, than a 25-year-old, who may have two offspring to support (Figure 11). Moreover, when childcare is excluded, a 60-year-old women works more overall than a 25-year-old woman.

However, the evidence suggests a slightly different explanation for why assistance from older women is important. Proponents of the grandmother hypothesis propose that the strength-intensive nature of human food gathering disadvantages young and increases the benefits of assistance from older women. The data presented here suggest that younger women are compromised in their food production by intensive childcare. Young babies are easiest to care for at a home base, and as a result, Machiguenga women increase their proximity to children and the amount of time they are in tactile contact with them when they are in the forest or other unsafe places (Kopischke 2001). This trade-off between food production and childcare may render the extra food provided by older women especially important.

The data on men are most problematic for the grandmother hypothesis and are most supportive of a cooperative division of labor by age and sex. First, men produce the bulk of the food, both agricultural and foraged. At their peak production, men produce about 12,000 calories per day, about 75% in garden foods with the remainder coming primarly from hunting and fishing. Women's peak production is closer to 5,000 calories per day, mostly in the form of garden products. Given that women do the bulk of food processing, men's caloric production from gardens is probably only a little higher than women's when all work is taken into account. Not only do older women play an important role in the energetics of reproduction by younger individuals, but so too do older men, perhaps even a greater role.

The data on men's meat acquisition are much more consistent with a macronutrient-balanced paternal provisioning strategy than with mating displays. Men do not hunt exclusively, but rather distribute their time among farming, fishing, and hunting. Farming produces many more calories per hour than do hunting or fishing (peak return rates for gardening exceed 10,000 calories per hour, whereas peak returns from hunting and fishing are between 1,000 and 2,000 calories per hour). As a result, the majority of men's surplus production comes from gardens. Informal interviews with Machiguenga men suggested that they supplemented garden foods with meat for nutritional reasons. A common comment was that children eating only manioc and plantains would not grow; they need to eat meat. They also reported that they varied their work effort seasonally, emphasizing hunting during the wet, fruiting season when animals are fat, and emphasizing fishing during the dry season when animals are parasitized and fish are more concentrated. Most fish acquired are small, weighing a kilogram or less, and as such are almost always consumed within residential clusters.

Data from other South American horticulturalists suggest that a diet composed of 70–80% garden products and 20–25% meat is very common. Hames (1989) argues that dietary protein is more efficiently produced through hunting and fishing than through horticulture for most Amazonian groups. He gives the proportion of total calories coming from gardening among the Achuar and the Yanomamo to be about 78% and those from hunting to be 16%, while hunting and fishing supply 78% of the dietary protein in the diet, and gardening supplies only 18%. Among the Machiguenga and the Piro, gardening, hunting, and fishing account for 70%, 9%, and 7% of the total acquired calories, respectively, with collecting providing the remainder. The proportions of hunted vs. fished meat tend to vary significantly among Amazonian forager-horticulturalists, but the proportion of total calories derived from meat, in one form or another, tends to vary less (Hames 1989), again suggesting nutrient complementarity. Taken together, these data suggest that men invest in children and grandchildren through food-related work effort, consistent with their age, the nutrient needs of their families, and seasonally varying rates of return from different activities.

It is not surprising therefore that Machiguenga and Piro tend to reside in extended family clusters comprising three generations of biologically related individuals. Those clusters eat most of their food in communal meals, and there is relatively little sharing among clusters. Large game animals and beer made from manioc are the most important foods that are shared among clusters. Yet, this sharing appears to be voluntary for the most part. In informal interviews, several Machiguenga men reported that sharing was completely voluntary and they could give to whomever they chose. Given this sharing pattern and the age-related changes in subsistence work and childcare exhibited by both men and women, it appears that a model in which lineage fitness is maximized by an age- and sex-related division of labor may be a reasonable approximation. However, any collaborative unit will be subject to some levels of free-riding, and as we have already mentioned, optimal time budgets for parents might not be optimal for children, and vice versa.

Future studies that examine time budgets, productivity, and distribution patterns of older males and females and of children in many populations will be necessary to illuminate key mechanisms responsible for the human pattern of long lifespans, long juvenile dependency, the sexual division of labor, age-graded specialization, and collaborative dynamics within and between households.

Michael Gurven is an assistant professor of anthropology at the University of California–Santa Barbara. He received his Ph.D. from the University of New Mexico in 2000. He has conducted fieldwork in Paraguay and Bolivia with Ache and Tsimane forager-horticulturalists. His research interests include intragroup cooperation and problems of collective action, and the application of life history theory to explaining human longevity, cognitive development, delayed maturation, and sociality. Since 2002, Gurven and Kaplan have co-directed the Tsimane Health and Life History Initiative, a five-year project to develop theory and test implications of different models of human life history evolution.

Hillard Kaplan is a professor of anthropology at University of New Mexico. He received his Ph.D. from the University of Utah in 1983. He has conducted fieldwork in Paraguay, Brazil, Botswana, and Bolivia. His research interests include evolutionary perspectives on life course development and senescence, and brain evolution. He has launched theoretical and empirical investigations into each of these areas, uniting evolutionary and economic approaches. He has applied human capital theory toward explaining human life history evolution, and the proximate physiological and psychological mechanisms governing fertility and parental investment in both traditional, high-fertility, subsistence economies and modern, low-fertility, industrial societies.

NOTES

1. Interestingly, the only case where net generation wealth flows are upward from younger to older individuals occurs in developed nations, as a result of public transfer programs, such as Social Security and Medicare. Even in developed nations, net within-family wealth flows are downward.
2. Although it might be the case that such laws also serve to reduce competition between adults and children for menial jobs, the justification for those laws is to provide children with the opportunity to improve their skills so that they will be able to find better jobs as adults.
3. We also hypothesize that the feeding niche specializing in large, valuable food packages, and particularly hunting, promotes cooperation between men and women and high levels of male parental investment because it favors sexual specialization in somatic investments and thus generates a complementarity between male and female inputs (Bird 1999). The economic and reproductive cooperation between men and women facilitates provisioning of juveniles, which both bankrolls their somatic investments and enables lower mortality during the juvenile and early adult periods. Cooperation between males and females also allows women to allocate more time to childcare, increasing both survival and reproductive rates. Finally, large packages also appear to promote interfamilial food sharing. Food sharing reduces risk of food shortfalls resulting from the vagaries of foraging, providing insurance against illness and against variance in family size owing to stochastic mortality and fertility. These buffers favor a longer juvenile period and higher investment in other mechanisms to increase lifespan.
4. The parameters in the Cobb-Douglas function for return rate, $A \times s_i(\text{age})^{\alpha} \times k_i(\text{age})^{\beta}$ [where $s_i(\text{age})$ and $k_i(\text{age})$ were parameterized as above], were chosen as:

Strength	*Skill*	α	β	A	$b_1\alpha + b_3\beta$	$b_2\alpha + b_4\beta$
low	low	0.1	0.1	40.00	0.34	0.009
low	high	0.1	0.7	2.60	1.24	0.024
high	low	0.7	0.1	2.63	1.46	0.045
high	high	0.7	0.7	0.18	2.36	0.060

5. This result is consistent with the time allocation to garden labor reported for a different group of Machiguenga by Baksh (1984).
6. Three other nonlinear models from Ratkowsky (1990) were considered (see text for model 1):

   $$Y_i = 1 / [a + (b \times X_i) + (c \times X_i^2)] \qquad \text{Model 2}$$

   $$Y_i = X_i / [a + (\mathrm{b} \times X_i) + (c \sqrt{X_t})] \qquad \text{Model 3}$$

   $$Y_i = \mathrm{a} + (\mathrm{b} \times X) + (c \times X^2) + d \times X^3 \qquad \text{Model 4}$$

   We made qualitative assessments of goodness-of-fit in the following three ways suggested by Huet et al. (1996): (*a*) plots of y vs. y, (*b*) plots of $\hat{e}$ vs. y and $\hat{e}$ vs. x, and (*c*) plots of $\hat{e}_i$ vs. $\hat{e}_{i-1}$. These examine whether the regression function is correct, whether the variance function is correct, and whether observations are independent. While models 1, 3, and 4 all give suitable fits to the data, models 1 and 3 are perhaps preferable to model 4 since they contain fewer estimated parameters. However, model 4 might be more appropriate for modeling high-strength/high-skill activities because the rate of decline continues to accelerate until death, whereas the other curves contain an inflection point which decreases the rate of decline for the most advanced ages.

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