The technology and neuroscience of capacity formation

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This paper begins the synthesis of two currently unrelated literatures: the human capital approach to health economics and the economics of cognitive and noncognitive skill formation. A lifecycle investment framework is the foundation for understanding the origins of human inequality and for devising policies to reduce it.

critical periods | sensitive periods | early childhood | Barker hypothesis

Introduction

Two currently unrelated bodies of research in economics point to the importance of the early years of childhood in shaping many adult outcomes. The "fetal programming literature surveyed by Gluckman and Hanson demonstrates that *in utero* environments affect adult health [1, 2]. Robert Fogel demonstrates an important empirical relationship between early nutrition and adult health [3, 4]. Barker demonstrates the predictive power of birthweight for the onset of adult coronary disease [5].

While the literature on the epidemiology of disease has taken a life cycle, developmental perspective, this approach has not yet made its way into the mainstream of health economics. For example, the influential analysis of Grossman focuses exclusive attention on adult health investment decisions, treating the health endowment determined in childhood and the preferences of the adult as parameters determined outside of his model [6, 7].

Parallel to the epidemiological literature, there is an emerging developmental literature in economics that demonstrates the importance of early environmental conditions on the evolution of adolescent and adult cognitive and noncognitive skills [8, 9]. These skills are important determinants of educational attainment, crime, earnings, and participation in risky behaviors [10]. Like the fetal programming literature, this literature documents critical and sensitive periods in the development of capacities. Unlike the fetal programming literature, it also considers environmental influences on development over the entire life cycle of the child and on into adulthood. Remediation of early disadvantage and resilience receive much more attention in this literature than in the literature on health economics. Each literature has much to learn from the other. Evidence on the importance of early environments on a spectrum of health, labor market, and behavioral outcomes suggests that common developmental processes are at work.

Cognitive and noncognitive skills — self-regulation, motivation, time preference, far-sightedness, adventurousness and the like — affect the evolution of health capital through choices made by parents and children. Grossman [7] and Smith [11] show that education is an important determinant of health disparities. The recent literature in economics shows the importance of personality and cognition in affecting educational choices. Aspects of personality and cognition play additional roles on health and healthy behaviors beyond their direct effect on education [10, 12].

Those with greater self-control and conscientiousness follow medical instructions and take care of themselves in a variety of ways. Certain personality types are at greater risk for mental health disorders [13]. Personality factors affect learning [14, 15]. Adverse health conditions impair learning [16]. Schultz and Ram [17] show that raising health promotes investment in human capital. People with longer horizons and lower rates of time preference invest more in themselves. Lower rates of time preference are associated with greater cognitive skills. Those with higher IQs are more farsighted (have lower time preference) because they envision future scenarios more clearly [18]. The recent literature on personality and preference formation establishes causal impacts of parental inputs and other environmental factors on cognitive and noncognitive skills [9, 13, 19]. The parameters of the Grossman model are the outputs of a developmental model.

The developmental focus adopted in this paper suggests new channels of policy influence to remediate well documented health disparities. Early childhood interventions that affect personality traits and cognitive skills that promote health can be effective policy tools in preventing and curing disease.

A simple investment framework unifies the literature on health and skill formation. It also reveals currently unexplored avenues for future research. The framework can be used to analyze synergies in producing health, cognitive skills, and noncognitive skills. An econometric approach based on dynamic latent variables operationalizes this framework. This approach recognizes the proxy nature of variables like birthweight, height, nutrition, IQ scores, and measures of personality and mental illness that play prominent roles in empirical work in epidemiology, education and health economics.

Human Diversity and Human Development

Any analysis of human development must reckon with nine facts. The first fact is that *ability matters*. A large number of empirical studies document that cognitive ability is a powerful determinant of wages, schooling, participation in crime and success in many aspects of social and economic life [10, 20, 21] and in health [22].

Second, *abilities are multiple in nature*. Noncognitive abilities (perseverance, motivation, time preference, risk aversion, self-esteem, self-control, preference for leisure) have direct effects on wages (controlling for schooling), schooling, teenage pregnancy, smoking, crime, performance on achievement tests and many other aspects of social and economic life [10, 13, 23]. They affect health choices (see the evidence on time preference and health in Grossman [7]). Social and emotional factors affect adult health [12].

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Abbreviations: CES, constant elasticity of substitution

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Third, *the nature versus nurture distinction, while traditional, is obsolete*. The modern literature on epigenetic expression and gene-environment interactions teaches us that the sharp distinction between acquired skills and ability featured in the early human capital literature is not tenable [1, 24, 25]. Additive "nature" and "nurture" models, while traditional and still used in many studies of heritability and family influence, mischaracterize gene-environment interactions. Recent analyses in economics that break the "causes" of birthweight into environmental and genetic components ignore the lessons of the recent literature. Genes and environment cannot be meaningfully parsed by traditional linear models that assign unique variances to each component. Abilities are produced, and gene expression is governed by environmental conditions [25, 26]. Behaviors and abilities have both a genetic and an acquired character. Measured abilities are the outcome of environmental influences, including *in utero* experiences, and also have genetic components.

The literature on fetal programming emphasizes the importance of the environment in causing gene expression that gives rise to susceptibility to different diseases, abilities and personality characteristics. See [1] for evidence on gene expression for disease and [25, 26] for evidence on environmental determinants of psychopathology and cognition. Some adverse early effects are more easily compensated than other effects. The concepts of remediation and resilience play prominent roles in economic analysis but are not featured in current discussions of health economics.[1]

Fourth, *ability gaps between individuals and across socioeconomic groups open up at early ages, for both cognitive and noncognitive skills. So do gaps in health status.* Figure 1 displays a prototypical pattern of a cognitive test score by age of child by socioeconomic status of the family.[2] Cunha, Heckman, Lochner and Masterov present many graphs showing the early divergence of child cognitive and noncognitive skills by age across children of parents with different socioeconomic status [29]. Levels of child cognitive and noncognitive skills are highly correlated with family background factors like parental education and maternal ability, which, when statistically controlled for, largely eliminate these gaps [29, 30]. Currie presents parallel evidence on child health [16]. Case, Lubotsky, and Paxson [31] show that family income gradients in child health status emerge early and widen with age (see Figure 2). Experimental interventions with long term followup confirm that changing the resources available to disadvantaged children improves adult outcomes on a number of dimensions. See the studies surveyed in [29] and [32].

Fifth, *for both animal and human species, there is compelling evidence of critical and sensitive periods in development*. Some skills or traits are more readily acquired at certain stages of childhood than other traits [8]. For example, on average, if a second language is learned before age 12, the child speaks it without an accent [33]. If syntax and grammar are not acquired early on, they appear to be very difficult to learn later on in life [34]. A child born with a cataract on the eye will be blind if the cataract is not removed within the first year of life.

Different types of abilities appear to be manipulable at different ages. IQ scores become stable by age 10 or so, suggesting a sensitive period for their formation below age 10 [35]. There is evidence that adolescent interventions can affect noncognitive skills [29]. This evidence is supported in the neuroscience that establishes the malleability of the prefrontal cortex into the early 20s [36]. This is the region of the brain that governs emotion and self-regulation. Rutter [25] and Rutter, Moffitt, and Caspi [26] present comprehensive summaries of age-dependent epigenetic and other gene-environment interactions for psychopathology — including aggression. Nagin and Tremblay show that early aggression predicts adult levels of criminality and violence [37].

On average, the later remediation is given to a disadvantaged child, the less effective it is. A study by Rutter and coauthors of adopted Romanian infants reared in severely deprived orphanage environments before their adoption supports this claim [38]. The later an orphan was rescued from the social and emotional isolation of the orphanage, the lower was his or her later cognitive performance. Secondary school classroom remediation programs designed to combat early cognitive deficits have a poor track record.

At historically funded levels, public job training programs and adult literacy and educational programs, like the GED, that attempt to remediate years of educational and emotional neglect among disadvantaged individuals, have a low economic return and produce meager effects for most persons. Much evidence suggests that returns to adolescent education for the most disadvantaged and less able are lower than the returns for the more advantaged [30, 39, 40].

The available evidence suggests that for many skills and capacities, later intervention for disadvantage may be possible, but that it is much more costly than early remediation to achieve a given level of adult performance [41]. Barker and coauthors document that if it is administered at the wrong developmental point, compensation for undernutrition can produce greater risk for later diabetes and heart disease [42]. To date, the health economics literature has not systematically studied the effectiveness of remediation for adverse early environments, although it evaluates the efficacy of treatments of diseases that may be influenced by adverse early environments.

Sixth, *despite the low returns to interventions targeted toward disadvantaged adolescents, the empirical literature shows high economic returns for remedial investments in young disadvantaged children*. See [43], the evidence in [29] and the papers they cite. This finding is a consequence of dynamic complementarity and self-productivity captured by the technology described in the next section. The evidence for interventions in low birth weight children suggests that early intervention can be effective [44]. Olds documents that perinatal interventions that reduce fetal exposure to alcohol and nicotine have substantial long-term effects on cognition, socioemotional skills and on health and have high economic returns [45].

Seventh, *if early investment in disadvantaged children is not followed up by later investment, its effect at later ages is lessened*. Investments at different stages of the life cycle are complementary and require follow up to be effective [9, 41].

Eighth, *the effects of credit constraints on a child's adult outcomes depend on the age at which they bind for the child's family*. Recent research summarized in [29, 30, 46] demonstrates the quantitative insignificance of family credit constraints in a child's college-going years in explaining a child's enrollment in college. Controlling for cognitive ability, under policies currently in place in American society, family income during a child's college-going years plays only a minor role in determining socioeconomic differences in college participation, although much public policy is predicated on precisely the opposite point of view. Controlling for ability, minorities are *more likely* to attend college than others despite their lower family incomes (see [47], and the references they cite). Augmenting family income or reducing college tuition at the stage of the life cycle when a child goes to college does not go far in compensating for low levels of early

[1] See, however, [27] and [28] for analyses of biological and psychobiological mechanisms for resilience.

[2] Permanent income is the measure of socioeconomic status in this figure. See [29] for the source of this figure and the precise definition of permanent income. The website of Cunha and Heckman [9] presents many additional graphs.

investment. It is the shortfall in adolescent abilities and motivations that account for minority college enrollment gaps. The gaps in health status by income evident in Figure 2 likely diminish once early environmental factors are controlled for, but this remains to be rigorously established.

Credit constraints operating in the *early* years have lasting effects on adult ability and schooling outcomes [48, 49, 50, 51]. Evidence on the persistent effects of early malnutrition *in utero* and in the early years on adult health is consistent with this evidence [1, 3, 4].

Ninth, *socioemotional (noncognitive) skills foster cognitive skills and are an important product of successful families and successful interventions in disadvantaged families. They also promote healthy behaviors*. Emotionally nurturing environments produce more capable learners. The Perry Preschool Program, which was evaluated by random assignment, did not boost participant adult IQ but enhanced the performance of participants on a number of dimensions, including scores on achievement tests, employment and reduced participation in a variety of social pathologies. See [52] and the figures and tables on the Perry program posted at the website for [9].

Perseverance and motivation are also important factors in explaining compliance with medical protocols. A large body of evidence suggests that a person's mood and attitudes as well as his social environment account, in part, for the ability of persons to ward off and overcome various diseases and to age gracefully [12]. The evidence that personality traits affect educational attainment [10] helps to explain how education, as a proxy, helps reduce disease gradients by socioeconomic class, as reported by Smith [11]. Figure 3 shows how greater cognitive and noncognitive skills reduce participation in smoking, a major health hazard [10].

A Model of Investment in Capacities

A simple model of capacity formation unifies this evidence. Agents are assumed to possess a vector of capacities at each age including pure cognitive abilities (e.g. IQ), noncognitive abilities (patience, self control, temperament, risk aversion, time preference), and health stocks. All capacities are produced by investment, environment and genes. These capacities are used with different weights in different tasks in the labor market and in social life more generally.[3]

The capacity formation process is governed by a multistage technology. Each stage corresponds to a period in the life cycle of a child. While the recent child development literature in economics recognizes stages of development [9, 29], the early literature on the economics of child development and the current literature on the economics of health do not [7, 53]. In the developmental approach, inputs or investments at each stage produce outputs at the next stage. Qualitatively different inputs can be used at different stages and the technologies can be different at different stages of child development.

The Ben-Porath model used by Grossman focuses on adult investments where time and its opportunity cost play important roles [6, 7]. For investments in childhood health, parents make decisions and child opportunity costs are less relevant [9]. The outputs at each stage in our technology are the changes in capacity at that stage. Some stages of the technology may be more productive in producing some capacities than other stages, and some inputs may be more productive at some stages than at other stages. The stages that are more effective in producing certain capacities are called "sensitive periods" for the acquisition of those capacities. If one stage alone is effective in producing a capacity, it is called a "critical period" for that capacity. Cunha and Heckman define these terms precisely [9].

The capacities produced at one stage augment the capacities attained at later stages. This effect is termed *self-productivity*. It embodies the ideas that capacities are self-reinforcing and cross-fertilizing and that the effects of investment persist. For example, emotional security fosters child exploration and more vigorous learning of cognitive skills. This has been found in animal species [54, 55, 56] and in humans (see [14, 15], interpreting the ability of a child to pay attention as a socioemotional skill). A higher stock of cognitive skill in one period raises the stock of next period cognitive skills. Higher levels of self-regulation and conscientiousness reduce health risks and avoid accidents. Higher levels of health promote learning. A second key feature of capacity formation is *dynamic complementarity*. Capacities produced at one stage of the life cycle raise the productivity of investment at subsequent stages. In a multistage technology, complementarity implies that levels of investments in capacity at different ages bolster each other. They are synergistic. Complementarity also implies that early investment should be followed up by later investment in order for the early investment to be productive. Together, dynamic complementarity and self-productivity produce multiplier effects which are the mechanisms through which capacities beget capacities. This dynamic process can account for the emergence of socioeconomic differentials in health documented by Smith [11] and Case, Lubotsky, and Paxson [31].

Dynamic complementarity and self-productivity imply an equity-efficiency trade-off for late child investments but not for early investments [9]. These features of the technology of capacity formation have consequences for the design and evaluation of public policies toward families. In particular, they show why the returns to late childhood investment and remediation for young adolescents from disadvantaged backgrounds are so low for many investments, while the returns to early investment in children from disadvantaged environments are so high.

Cunha and Heckman [9] and Carneiro, Cunha and Heckman [57] formalize these concepts in an overlapping generations model. There is evidence on intergenerational linkages in health, personality and skill formation [16, 57, 58].

Consider a household which consists of an adult parent and his/her child. Take parental stocks of skills as given. In a proper overlapping generations model, as developed in [57] and the website for [9], investment in parents is modeled, explaining the intergenerational transmission of health, personality and cognition.

Altruistic parents invest in their children. Let I_t denote parental investments in child skill when the child is t years-old, where $t = 1, 2, \ldots, T$. The first stage can be *in utero* investment. The output of the investment process is a skill vector. The parent is assumed to fully control the investments in the skills of the child, whereas in reality, as a child matures, he gains much more control over the investment process.[4] Thus, children with greater emotional skills and conscientiousness are less likely to be involved in risky teenage activities (see Figure 3 and the evidence in [10]). For expositional simplicity we ignore investments in the child's adult years. We also keep government inputs (e.g., schooling) implicit. They can be modeled as a component of I_t. It would be desirable to merge the model of parental investment with the model of adult investment, but that is beyond the scope of this paper. I leave this task for another occasion.

At conception, the child receives genetic and environmental initial conditions θ_1. As documented by Gluckman and Hanson [1] and Rutter [25], gene expression is triggered by environmental conditions. Let h denote parental capacities (e.g., IQ, genes, education, income,

[3] Cunha, Heckman, Lochner, and Masterov [29] propose a model of comparative advantage in occupational choice to supplement their model of skill formation.

[4] A sketch of such a model is discussed in [57].

etc.). These are products of their own parents' investments and genes. At each stage t, let θ_t denote the vector of capacities. The technology of capacity production when the child is t years old is

$$\theta_{t+1} = f_t\left(h, \theta_t, I_t\right), \qquad [1]$$

for $t = 1, 2, \ldots, T$. For analytical convenience, f_t is assumed to be strictly increasing and strictly concave in I_t, and twice continuously differentiable in all of its arguments.

Technology (1) is written in recursive form. Substituting in (1) for θ_t, θ_{t-1},..., repeatedly, one can rewrite the stock of capacities at stage $t+1$, θ_{t+1}, as a function of all past investments:

$$\theta_{t+1} = m_t\left(h, \theta_1, I_1, \ldots, I_t\right), t = 1, \ldots, T. \qquad [2]$$

Dynamic complementarity arises when $\partial^2 f_t\left(h, \theta_t, I_t\right) / \partial\theta_t \partial I_t' > 0$, i.e., when stocks of capacities acquired by period $t-1$ (θ_t) make investment in period t (I_t) more productive. Such complementarity explains why returns to educational investments are higher at later stages of the child's life cycle for more able, more healthy and more motivated children (those with higher θ_t). Students with greater early capacities (cognitive, noncognitive and health) are more efficient in later learning of both cognitive and noncognitive skills and in acquiring stocks of health capital. The evidence from the early intervention literature suggests that the enriched early preschool environments provided by the Abecedarian, Perry and CPC interventions promote greater efficiency in learning in school and reduce problem behaviors [29, 32]. Enriched early environments produce healthier babies [1, 59].

Self-productivity arises when $\partial f_t\left(h, \theta_t, I_t\right) / \partial\theta_t > 0$, i.e., when higher levels of capacities in one period create higher levels of capacities in the next period. For capacity vectors, this includes own and cross effects. The joint effects of self-productivity and dynamic complementarity help to explain the high productivity of investment in disadvantaged young children but the lower return to investment in disadvantaged adolescent children for whom the stock of capacities is low and hence the complementarity effect is lower.

This technology explains the evidence that the ability of the child to pay attention affects subsequent academic achievement. Healthier children are better learners [16]. This technology also captures the critical and sensitive periods in humans and animals documented for a number of aspects of development [8].

Suppose for simplicity that $T = 2$. In reality, there are many stages in childhood, including preconception and *in utero* stages. Assume for expositional simplicity that θ_1, I_1, I_2 are scalars.[5] The adult stock of capacity, h' ($= \theta_3$), is a function of parental characteristics, initial conditions and investments during childhood I_1 and I_2:

$$h' = m_2\left(h, \theta_1, I_1, I_2\right). \qquad [3]$$

The conventional literature in economics [53] assumes only one period of childhood when it addresses childhood at all. It does not distinguish between early investment and late investment. The conventional specification is a special case of the technology (3), where

$$h' = m_2\left(h, \theta_1, \gamma I_1 + (1-\gamma) I_2\right) \qquad [4]$$

and $\gamma = 1/2$. Adult capacities do not depend on how investments are distributed over different periods of childhood, just their total level.

The polar opposite of perfect substitution is perfect complementarity:

$$h' = m_2\left(h, \theta_1, \min\left\{I_1, I_2\right\}\right). \qquad [5]$$

In this specification of the technology, adult capacities critically depend on how investments are distributed over time. For example, if investment in period one is zero, $I_1 = 0$, then it does not pay to invest in period two. If late investment is zero, $I_2 = 0$, it does not pay to invest early. For the technology of capacity formation defined by (5), the best strategy is to distribute investments evenly, so that $I_1 = I_2$. Complementarity has a dual face. It is essential to invest early to get satisfactory adult outcomes. But it is also essential to invest late to harvest the fruits of the early investment.

A general technology that nests (4) and (5) is a standard CES:

$$h' = m_2\left(h, \theta_1, \left[\gamma\left(I_1\right)^{\phi} + (1-\gamma)\left(I_2\right)^{\phi}\right]^{\frac{1}{\phi}}\right) \qquad [6]$$

for $\phi \leq 1$ and $0 \leq \gamma \leq 1$. The CES share parameter γ is a *capacity multiplier*. It reveals the productivity of early investment not only in directly boosting h' (through self-productivity) but also in raising the productivity of I_2 by increasing θ_2 through first-period investments. Thus I_1 directly increases θ_2 which in turn affects the productivity of I_2 in forming h'. γ captures the net effect of I_1 on h' through both self-productivity and direct complementarity.

The elasticity of substitution $1/(1-\phi)$ is a measure of how easy it is to substitute between I_1 and I_2. For a CES technology, ϕ represents the degree of complementarity (or substitutability) between early and late investment in producing capacity. The parameter ϕ governs how easy it is to compensate for low levels of stage 1 capacity in producing later adult capacity. See the analysis of this model in [9, 29].

When ϕ is small, low levels of early investment I_1 are not easily remediated by later investment I_2. The other face of CES complementarity is that when ϕ is small, high early investment should be followed with high late investment if the early investment is to be harvested. In the extreme case when $\phi \to -\infty$, (6) converges to (5). This technology explains why returns to education are low in the adolescent years for disadvantaged (low h, low I_1, low θ_2) adolescents but are high in the early years. Without the proper foundation for learning (high levels of θ_2) in technology (1), adolescent interventions have low returns. Bad initial conditions that create physical and mental impairments produce persistently less healthy adults [1, 5, 42].

The Optimal Lifecycle Profile of Capacity Investments

Using technology (6), Cunha and Heckman [9] determine how the ratio of early to late investments varies as a function of ϕ and γ as a consequence of parental choices under different market arrangements. Let w and r denote wage and interest rates, respectively, in a stationary environment. At the beginning of adulthood, the parent draws the initial level of skill of the child, θ_1, from the distribution $J(\theta_1)$, and receives bequest b. The endowments for the parent are the parental capacities, h, the parental financial resources, b, and the initial capacity level of the child, θ_1. Let c_1 and c_2 denote the consumption of the household in the first and second period of the lifecycle of the child. The parent decides how to allocate the resources among consumption and investments at different periods as well as bequests to their child b' which may be positive or negative. Assuming that human capital (parental and child) is scalar, the parent's budget constraint is:

$$c_1 + I_1 + \frac{c_2 + I_2}{(1+r)} + \frac{b'}{(1+r)^2} = wh + \frac{wh}{(1+r)} + b. \qquad [7]$$

Let β denote the utility discount factor and δ be parental altruism toward the child. Let $u(\cdot)$ denote the utility function. The recursive

[5] Cunha et al. [29] analyze the vector case. See also the supporting material on the website for [9].

formulation of the problem of the parent is:

$$V(h, b, \theta_1) = \max \left\{ u(c_1) + \beta u(c_2) + \beta^2 \delta E \left[V\left(h', b', \theta_1'\right) \right] \right\}. \quad [8]$$

The problem of the parent is to maximize (8) subject to (7), and technology (6). This bare-bones analysis abstracts from the effects of parental investment on time preference and risk preference. Space constraints preclude the development of a more general model.

When $\phi = 1$, so early and late investment are perfect CES substitutes, it is always possible to remediate early disadvantage. However, it is not always economically feasible to do so. The price of early investment is \$1. The price of late investment is $\$1/(1+r)$. The amount of human capital (including health capital) produced from one unit of I_1 is γ, while $\$(1+r)$ of I_2 produces $(1+r)(1-\gamma)$ units of human capital. Two forces act in opposite directions. High productivity of initial investment (the skill multiplier γ) drives the parent toward making early investments. The interest rate drives the parent to invest late. It is optimal to invest early if $\gamma > (1-\gamma)(1+r)$. Epidemiologists are prone to neglect the costs of remediation when they demonstrate its possibilities.

As $\phi \to -\infty$, the optimal investment strategy sets $I_1 = I_2$. In this case, investment in the young is essential. However, later investment is needed to harvest early investment. On efficiency grounds, early disadvantages should be perpetuated, and compensatory investments at later ages are economically inefficient.

For an interior solution, the optimal ratio of early to late investment is

$$\frac{I_1}{I_2} = \left[\frac{\gamma}{(1-\gamma)(1+r)} \right]^{\frac{1}{1-\phi}}. \quad [9]$$

Figure 4 plots the ratio of early to late investment as a function of the skill multiplier γ under different values of the complementarity parameter ϕ, assuming $r = 0$.

When CES complementarity is high, the skill multiplier γ plays a limited role in shaping the optimal ratio of early to late investment. High early investment should be followed by high late investment. As the degree of CES complementarity decreases, the role of the capacity multiplier increases, and the higher the multiplier, the more investment should be concentrated in the early ages.

In a model with perfect credit markets, optimal investment levels are not affected by parental wages or endowments, or the parameters that characterize the utility function $u(\cdot)$.[6] Note, however, that even in this "perfect" credit market setting, parental investments depend on parental capacities as encapsulated in h because these characteristics affect the returns to investment. Cunha and Heckman [9] analyze the effects of alternative credit market arrangements on optimal investment profiles.

Cognitive, Noncognitive and Health Formation

This framework readily accommodates capacity vectors. Child development is not just about cognitive skill formation although a lot of public policy analysis focuses solely on cognitive test scores to the exclusion of physical health and personality factors. Let θ_t denote the vector of capacities, i.e., cognitive skills, noncognitive skills and health capacities: $\theta_t = \left(\theta_t^C, \theta_t^N, \theta_t^H\right)$. Let I_t denote the vector of investment in cognitive, noncognitive and health capacities: $I_t = \left(I_t^C, I_t^N, I_t^H\right)$. Use $h = \left(h^C, h^N, h^H\right)$ to denote parental cognitive, noncognitive and health capacities. At each stage t, one can define a recursive technology for cognitive skills $(k = C)$, noncognitive skills, $(k = N)$, and health $(k = H)$:

$$\theta_{t+1}^k = f_t^k \left(\theta_t^C, \theta_t^N, \theta_t^H, I_t^k, h^C, h^N, h^H\right), \; k \in \{C, N, H\}. \quad [10]$$

Technology (10) allows for cross-productivity effects: cognitive skills may affect the accumulation of noncognitive skills and vice versa. Health capacities facilitate the accumulation of cognitive and noncognitive skills. These technologies also allow for critical and sensitive periods to differ across capacity investments. Cognitive and noncognitive skills and health capacities determine costs of effort, time preference and risk aversion parameters. By investment choices, parents shape preferences that govern the choices of children in a variety of dimensions.

Accounting for preference formation explains the success of many early childhood programs targeted to disadvantaged children which do not permanently raise IQ, but which permanently boost social performance.[7] Conscientiousness, farsightedness, and persistence, as well as other personality features, affect participation in risky activities, including smoking [10, 13].

Estimating the Technology: Accounting for the Proxy Nature of Inputs and Outputs

Cunha and Heckman [60] and Cunha, Heckman and Schennach [19] estimate versions of technology (10) and show that many of the proxies for investment and outcomes that are used in the child development and health literatures have low signal-to-noise ratios. Systematically accounting for measurement error greatly affects estimates of technologies of skill formation and other behavioral relationships. Smoking is an error-laden proxy for noncognitive skill [10]. Many papers in health economics rely on smoking (and other behaviors) as proxies for time preference (see the survey in [7]). The empirical literature on child development suggests that accounting for the proxy nature of smoking will improve the explanatory power and interpretability of the estimates of time preference on health choices.

Summary

This paper begins the process of synthesizing the modern literature on the economics of child development and the economics of health. A large literature documents the importance of the early years in determining adult capacities of cognition, motivation and health. A common developmental process appears to be in operation where cognitive and noncognitive skills and health capacities at one stage of childhood cross-fertilize the productivity of investment at later stages. Using the technology of capacity formation developed by Cunha and Heckman [9], one can organize and interpret a large body of evidence from diverse literatures. Accounting for the early emergence of abilities, personality parameters and health stocks redirects the attention of health economists to the early years and to models of parental investment instead of toward models of adult investment as in Grossman [7].

Simple economic models show the importance of accounting for early and late investments and for examining the technological possibilities and economic costs of late remediation for early environmental influence. Frameworks that account for the proxy nature of the measurements of inputs and outputs hold much promise, both in health economics and in the economics of child development.

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[6] We refer to parental resources specific to a given generation. There is danger of confusion because, under the stationary assumption, the wage of the parent and the wage of the child are the same. It is the wage of the child (the return) that governs investment. See [9], where this point is developed more explicitly.

[7] The Abecedarian early intervention program permanently boosted adult IQ [29].

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Fig. 1. Children of the NLSY average standardized score for PIAT math by family permanent income quartile. Source: Full sample of the Children of the National Longitudinal Survey of Youth.

Fig. 2. Health and income for children and adults U.S. national health interview survey 1986-1995. Reprinted from [31] with permission from the authors.

Fig. 3. Probability of daily smoking by age 18, males by decile of cognitive and noncognitive factor. The highest decile of cognitive and noncognitive ability is "10." "1" is the lowest decile. Reprinted from [10] ©2006, University of Chicago Press.

Fig. 4. Ratio of early to late investment in human capital as a function of the skill multiplier for different values of complementarity. Reprinted from [29] with permission from Elsevier.

Figure 1

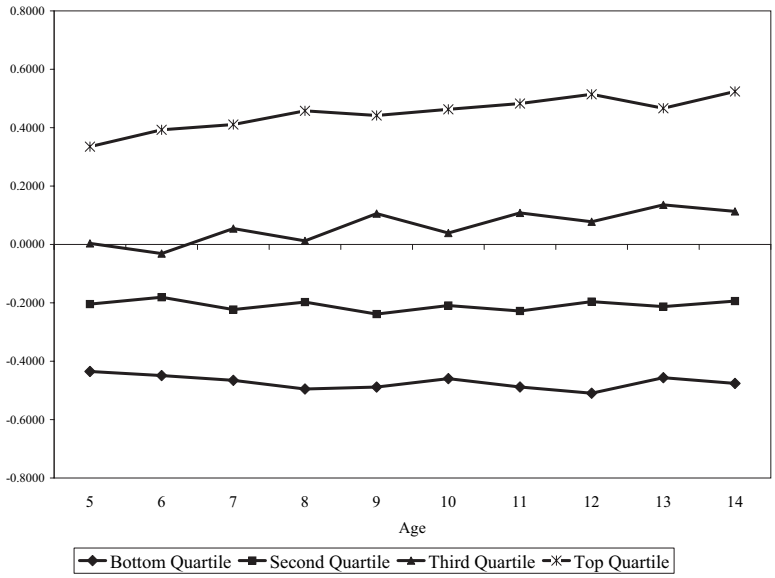

Figure 2

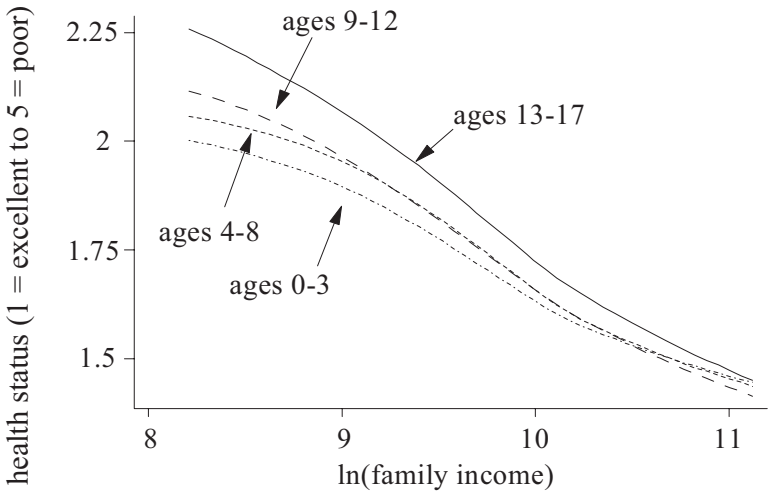

Figure 3

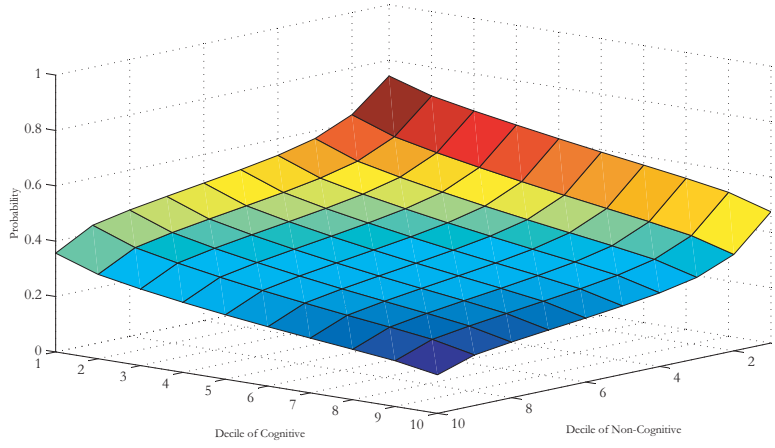

Figure 4