The Technology and Neuroscience of Skill and Health Formation

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Economic Causes and Consequences of Population Aging
Robert Fogel 80th Birthday Celebration
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Introduction

- The success of modern economies depends in part on well-educated, healthy and adaptable workers who are capable of learning new skills so that they remain competitive in a continually changing global market.
- Families are the major producers of the skills that promote schooling and adaptability.
- A large body of research in neuroscience and psychology shows that the early years are foundational for a full range of human competencies and capacities and are a period of heightened sensitivity to the effects of both positive and negative experiences.

Introduction

- In a parallel fashion, studies of human capital formation indicate that the quality of the early childhood environment is a strong predictor of adult productivity, and that early enrichment for disadvantaged children increases the probability of later economic success.
- Research also shows the importance of the early years in shaping growth, human health and the foundations of adult physical well being.

Introduction

- Although explanatory mechanisms for interpreting these correlations are still being developed, recent advances in neuroscience and physiology are illuminating, as they demonstrate the extent to which early experience influences the development of neural circuits that mediate cognitive, linguistic, emotional, and social capacities.
- Today we discuss a body of research on the development of humans and animals that cuts across disciplines.

Introduction

- We discuss recent evidence on the technology of skill formation that helps to unite the evidence within a unified economic and econometric framework.
- This research provides a framework for integrating diverse evidence from the field of child development and economics within a unified framework.
- Move beyond "treatment effects" reported in the literature to develop a general interpretive framework that can be used for policy evaluation.

Introduction

- There is a striking convergence of four core concepts that have emerged from decades of mutually independent research in economics, neuroscience, and developmental psychology.
- First, the architecture of the brain and the process of skill formation are both influenced by an inextricable interaction between genetics and individual experience.
- Second, both the mastery of skills that are essential for economic success and the development of their underlying neural pathways follow hierarchical rules in a bottom-up sequence such that later attainments build on foundations that are laid down earlier.

Introduction

- Third, cognitive, linguistic, social, physiological and emotional competencies are interdependent, all are shaped powerfully by the experiences of the developing child, and all contribute to success in the workplace, in schools and in society at large.
- Fourth, although adaptation continues throughout life, human abilities are formed in a predictable sequence of sensitive periods, during which the development of specific neural circuits and the behaviors they mediate are most plastic, and therefore optimally receptive to environmental influences.

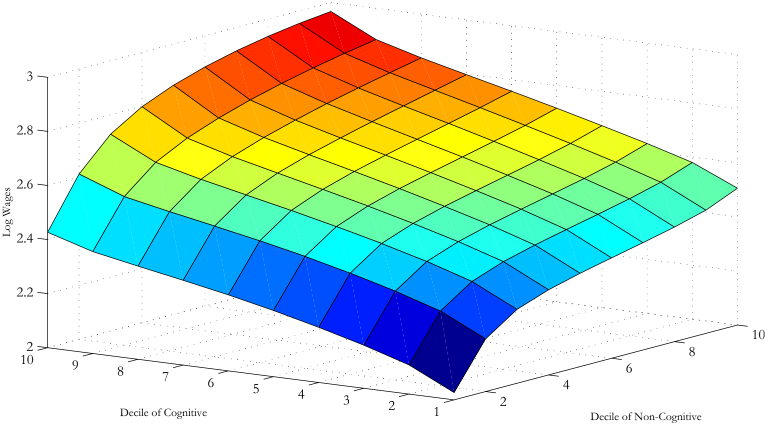
Early Experience Shapes the Foundation for Adult Productivity

- Virtually every aspect of early human development, from the brain's evolving circuitry to the child's capacity for empathy, is affected by the environments and experiences that are encountered in a cumulative fashion, beginning in the prenatal period and extending throughout the early childhood years.
- Extensive evidence indicates that cognitive, social, and emotional capacities play important roles in the attainment of adult economic productivity, and all are shaped in part by early life experiences.
- High levels of socioemotional skills foster exploration, curiosity and learning.
- Cognitive and noncognitive abilities are produced by families and affect later acquisition in a dynamic fashion.

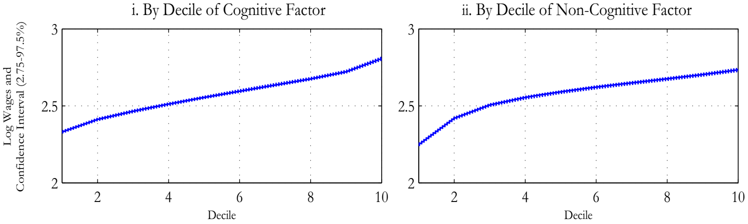
Evidence on the Importance of Cognitive and Noncognitive Skills

- Recent research has shown that earnings, employment, labor force experience, college attendance, teenage pregnancy, participation in risky activities and participation in crime strongly depend on cognitive and noncognitive abilities. (Bowles and Gintis, 1976; Edwards, 1976; Klein, Spady, and Weiss, 1991; Heckman and Rubinstein, 2001; Heckman, Stixrud, and Urzua, 2006).
- By noncognitive abilities, we mean socioemotional regulation, time preference and personality factors.
- Some would include "character" in the mix.
- Consider the following evidence from a recent study by Heckman, Stixrud and Urzua (2006).

Mean log wages by age 30 (males)

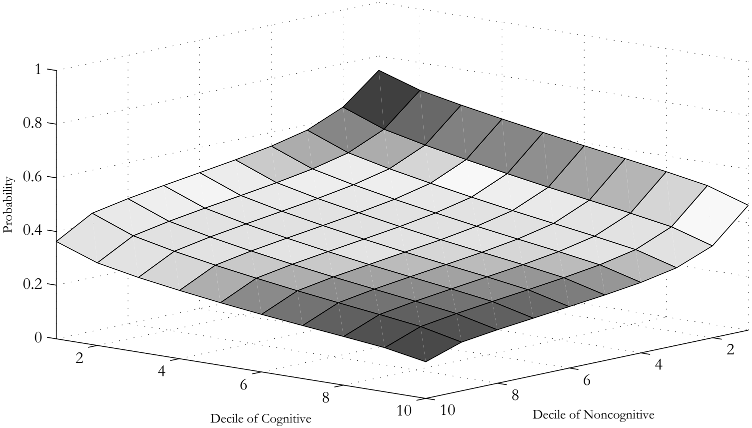


Mean log wages by age 30 (males) (cont.)

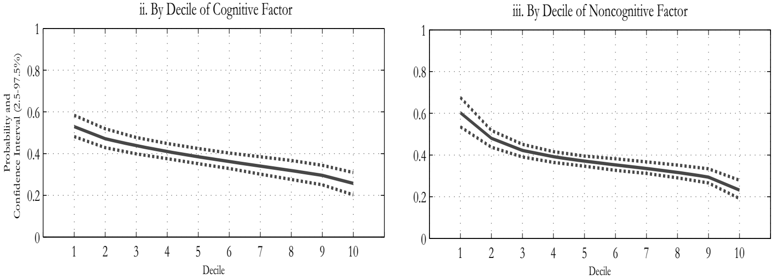


Notes: The data are simulated from the estimates of the model and our NLSY79 sample. We use the standard convention that higher deciles are associated with higher values of the variable. The confidence intervals are computed using bootstrapping (50 draws).

Probability of daily smoking by age 18 (males)

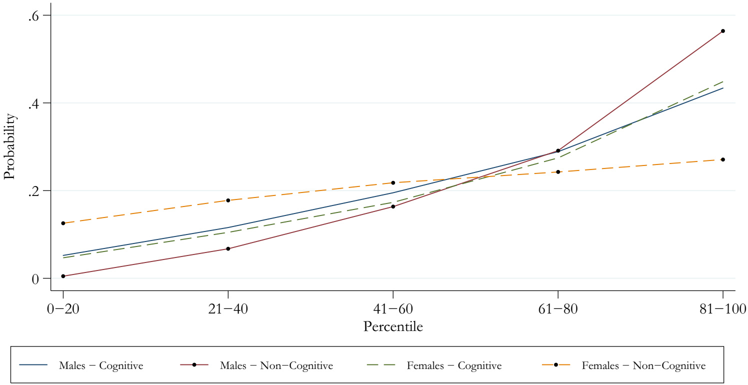


Probability of daily smoking by age 18 (males) (cont.)



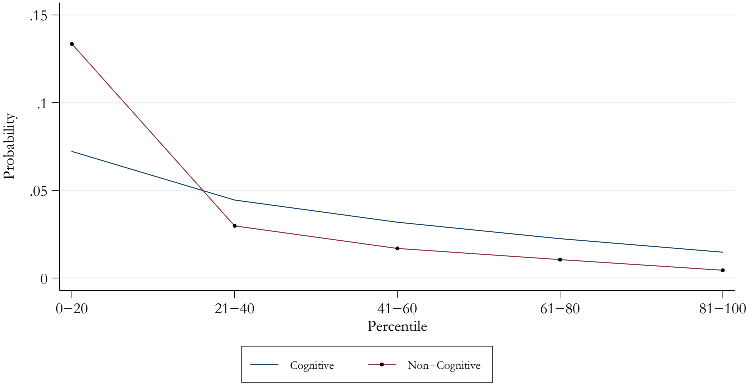
Notes: The data are simulated from the estimates of the model and our NLSY79 sample. We use the standard convention that higher deciles are associated with higher values of the variable. The confidence intervals are computed using bootstrapping (200 draws).

Probability of being a 4-year college graduate, by ability



Note: This figure plots the probability of a given behavior associated with moving up in one ability distribution for someone after integrating out the other distribution. For example, the lines with markers show the effect of increasing noncognitive ability after integrating the cognitive ability. Source: Heckman, Stixrud, and Urzua (2006).

Ever been in jail by age 30, by ability (males)



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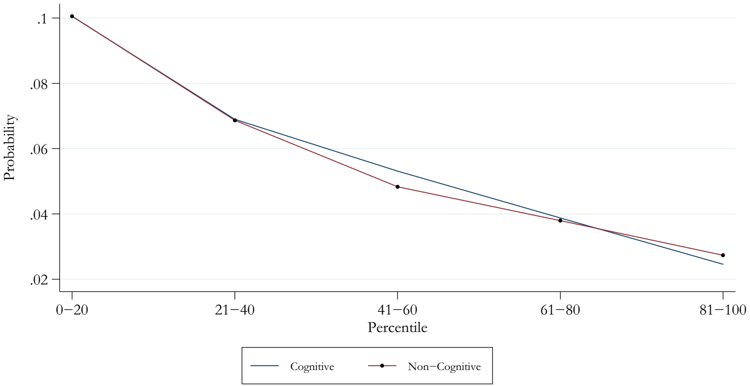
Probability of being single with children (females)



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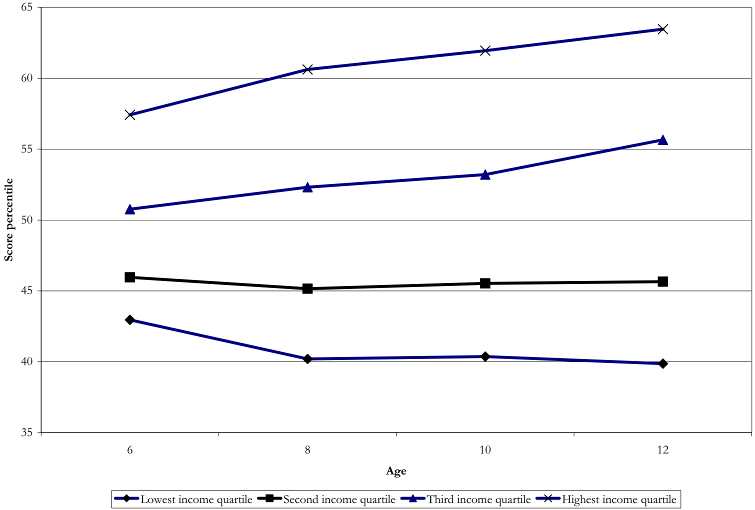
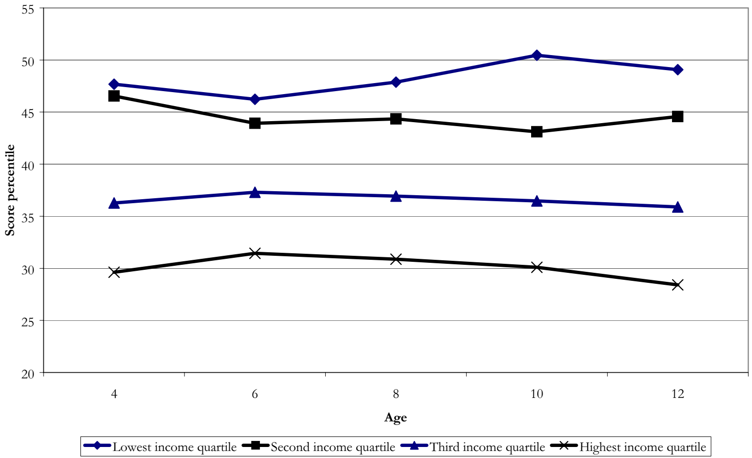
Evidence on the Importance of Cognitive and Noncognitive Skills

- Gaps in the abilities that play such an important role in determining diverse adult outcomes open up early across income groups.
- Schooling after the second grade plays only a minor role in alleviating these gaps.
- Measures of schooling quality play only a minor role in alleviating or exacerbating the gaps after the first few years of schooling (Coleman Report, 1966).

Average percentile rank on PIAT-Math score, by income quartile



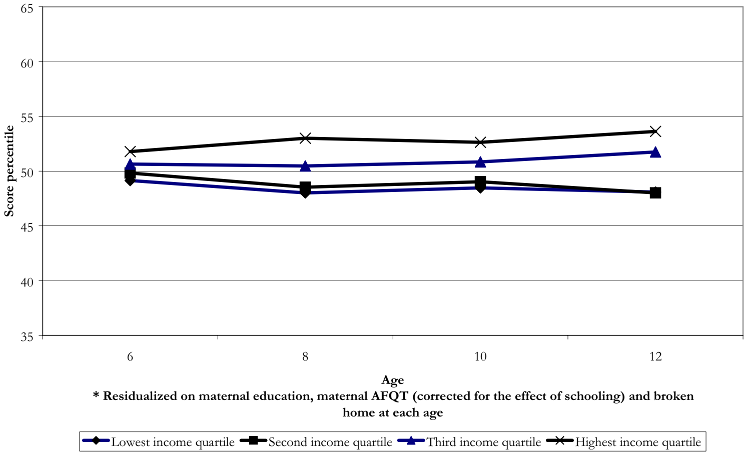
Average percentile rank on anti-social score, by income quartile



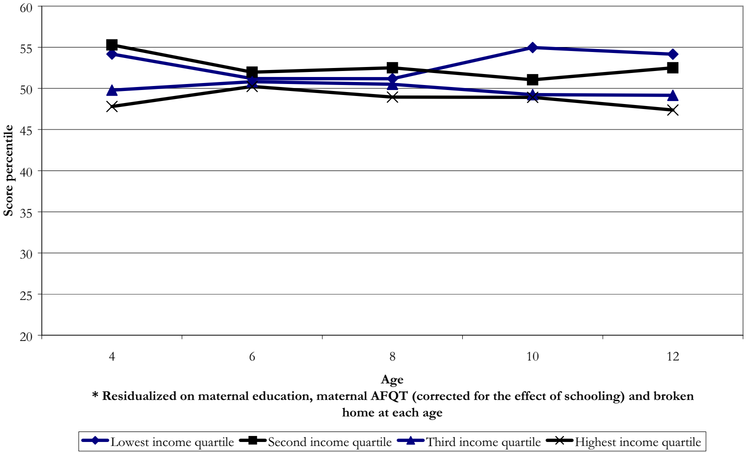
Evidence on the Importance of Cognitive and Noncognitive Skills

- Once we control for early family background factors using regression, the gaps in ability greatly diminish.

Residualized average PIAT-Math score percentiles, by income quartile



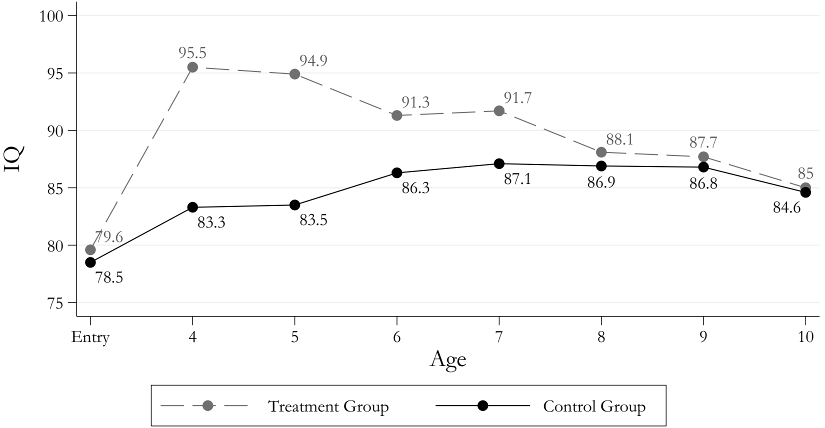
Residualized average anti-social score percentile, by income quartile



Evidence on the Importance of Cognitive and Noncognitive Skills

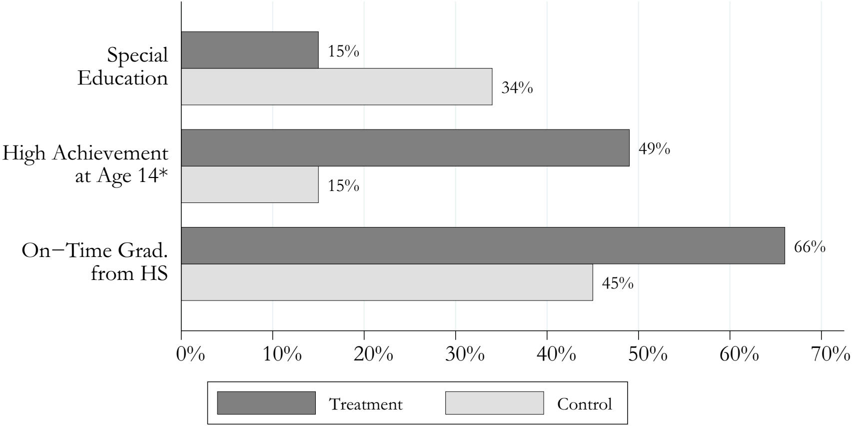
- Experiments that enrich the early environments of disadvantaged children show that the effects of early environments on adolescent and adult outcomes are causal. Improvements in family environments enhance outcomes and affect both cognitive and noncognitive skills.
- Noncognitive skills are an important channel of improvement.

Perry preschool program: IQ, by age and treatment group



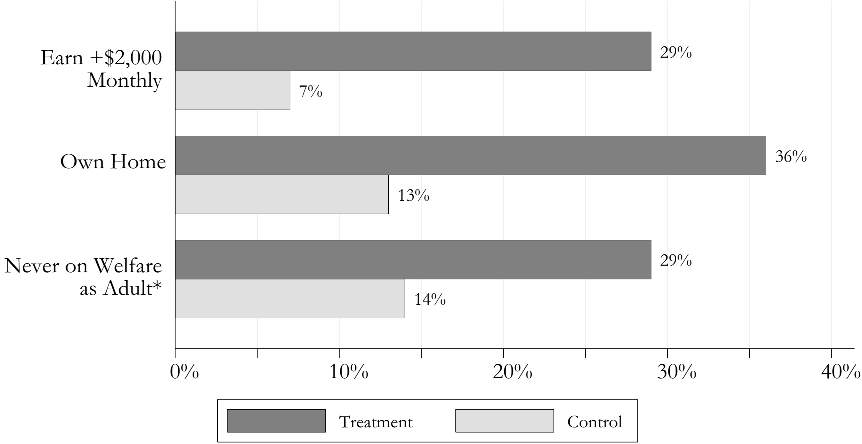
Source: Perry Preschool Program

Perry preschool program: educational effects, by treatment group



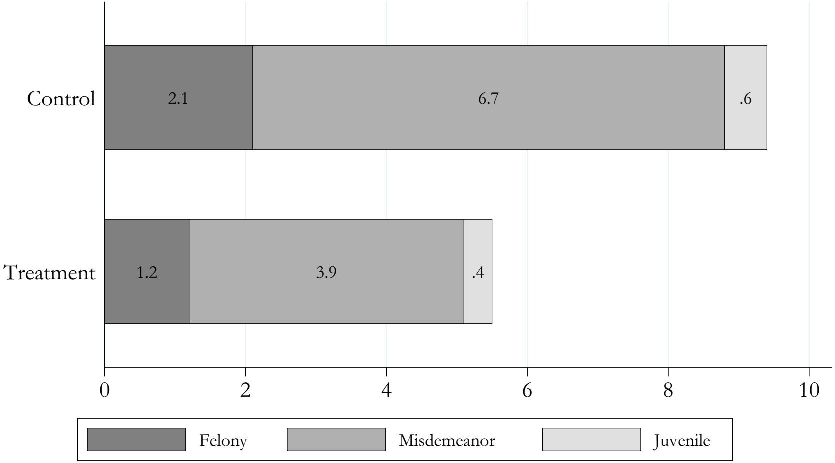
Source: Barnett (2004).
Notes: *High achievement defined as performance at or above the lowest 10th percentile on the California Achievement Test (1970).

Perry preschool program: economic effects at age 27, by treatment group



Source: Barnett (2004). *Updated through Age 40 using recent Perry Preschool Program data, derived from self−report and all available state records.

Perry preschool program: economic effects at age 27, by treatment group

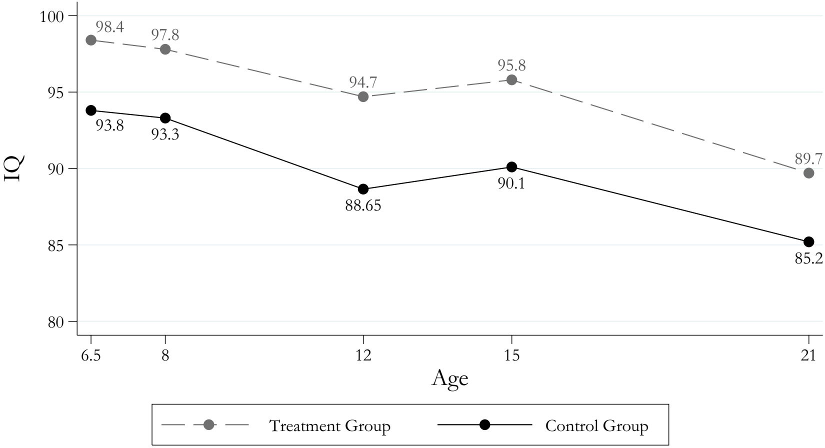


Source: Perry Preschool Program. Juvenile arrests are defined as arrests prior to age 19.

Evidence on the Importance of Cognitive and Noncognitive Skills

- If we start early enough and intensively enough, we can also raise IQ.

Abecedarian IQ scores over time



Source: Barnett (2004).

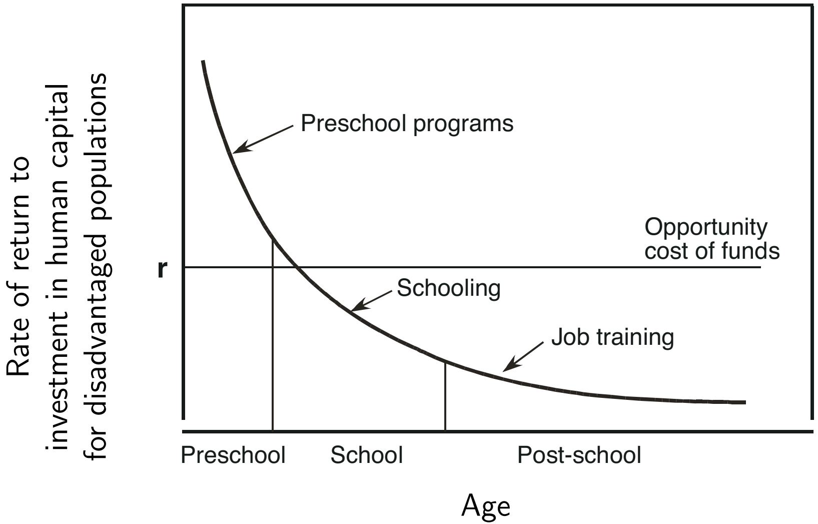
Evidence on the Importance of Cognitive and Noncognitive Skills

- Several observations about the evidence from intervention studies are relevant.
- First, skills beget skills. All capabilities are built on a foundation of capacities that are developed earlier.

Evidence on the Importance of Cognitive and Noncognitive Skills

- Second, early intervention lowers the cost of later investment.
- Public job training programs, adult literacy services, prisoner rehabilitation programs, and education programs for disadvantaged adults at current levels of expenditure have yielded low economic returns, with the returns for males often being negative.
- Moreover, for several studies in which later intervention showed benefits, the performance of these children was still behind the performances of children who experienced earlier interventions in the preschool years.
- If the base is weak, the return to later investment is low.

Returns to a unit dollar invested



Evidence on the Importance of Cognitive and Noncognitive Skills

- Although investments at later stages realize relatively less return overall, such investments are still clearly beneficial.
- Indeed, the advantages gained from effective early interventions are sustained best when they are followed by continued high quality learning experiences.
- The technology of skill formation shows that the returns on school investment are higher for persons with higher ability, where ability is formed in the early years.
- Due to dynamic complementarity, early investments must be followed by later investments if maximum value is to be realized.

Evidence on the Importance of Cognitive and Noncognitive Skills

- The most convincing data come from high quality intervention programs, which are not representative of the effectiveness of a wide range of services typically available to children from disadvantaged environments.
- These studies are often based on small samples with diverse populations. They are not even representative of the target populations for proposed interventions.
- We have synthesized this evidence and have shown that, properly analyzed, the experiments show strong effects for both boys and girls.

Evidence on the Importance of Cognitive and Noncognitive Skills

- Ethical, practical, and cost considerations impose stringent limitations on how far research on humans can be pursued in rigorously controlled studies.

Evidence on sensitive and critical periods from animal and human species

- Knudsen (2004) shows that early experiences modify the biochemistry and architecture of neural circuits. (See Knudsen, Heckman, Cameron and Shonkoff, 2006)
- When this modification occurs during a limited time frame, it is called a sensitive period.
- When the modification occurs during a limited time frame and it is crucial for normal development, it is called a critical period.

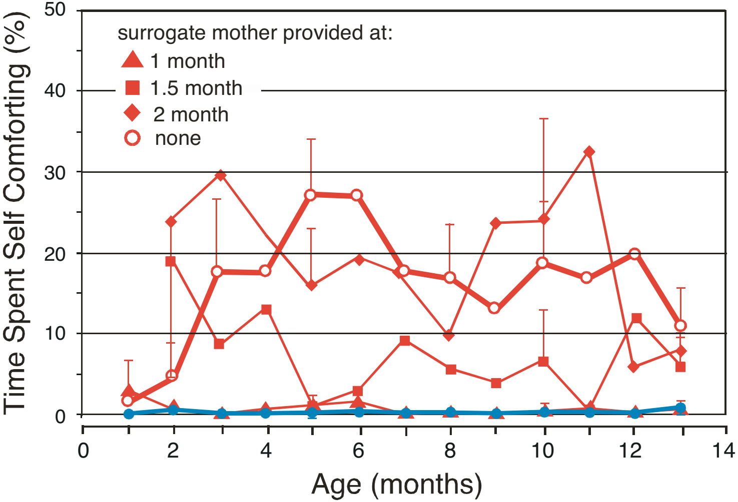
Evidence on sensitive and critical periods from animal and human species

- Sensitive and critical periods have been documented extensively for many phenomena, including:
  1. monkey mothering
  2. rat mothering
  3. binocular vision in the cortex of mammals
  4. filial imprinting in the forebrain of ducks and chickens
  5. language acquisition in humans

Evidence from Other Species that Early Experience Shapes Temperament and Social Development

- One of the most salient examples is the powerful influence of early interactions between an infant and its mother in shaping the temperament and social behavior of the developing animal.
- Consider removing a monkey from its mother and replacing it–with various delays–with surrogates, including one intervention with no mother replacement.

Studies of monkeys



Consequences of Early Affiliative Bond Disruption in Monkeys

- The nature and severity of the effects of removing the mother changed with the age of the infants at the time of separation.
- Once the infants had reached 6 months old, removal of the mother from the group had no apparent impact on the infant.
- In contrast, infants who had their mothers removed at one month of age exhibited acute withdrawal and depression, followed by increased seeking of social comfort from other monkeys and a variety of atypical social behaviors, many of which persisted into adulthood.

Consequences of Early Affiliative Bond Disruption in Monkeys

- Attempts to remediate the social and emotional consequences of early affiliative bond disruption generally had limited impact.

Consequences of Early Affiliative Bond Disruption in Monkeys

- Studies in rodents also demonstrate that differences in affiliative behavior experienced early in life can have long-term effects on social behaviors and anxiety in adulthood.
- These findings — that both differences in, and disruptions of, close affiliative bonds early in life can have life-long effects on the development of social behaviors — raise important concerns about the extent to which analogous early life experiences influence human development.
- Extensive animal research also demonstrates the existence of sensitive periods, usually early in life, when the systems underlying the development of social skills are particularly plastic, followed by a period during which this plasticity decreases with age.

A Sensitive Period for Shaping the Temperament of Rodents

- Certain aspects of the temperament of individual rats can be altered profoundly by early social experience.
- For example, rat pups that are cared for during the first week after birth by a mother who grooms them extensively (high-grooming) and nurses them in a way that facilitates their access to milk (arched-back nursing) become more adventurous, less fearful, less anxious, and less reactive to stress than rat pups raised by a mother who does not act in this manner.

A Sensitive Period for Shaping the Temperament of Rodents

- These emotional traits, shaped by experience during this sensitive period, have positive effects on the development of the individual's social and cognitive behaviors that persist into adulthood.
- Cross-fostering experiments show that the transmission of these traits is dominated primarily by early experience, not by genetics.
- Rats born to low-grooming mothers (non-attentive, little grooming, no arched-back nursing), but raised by high-grooming mothers, become themselves calm, adventurous adults and high-grooming parents.

A Sensitive Period for Shaping the Temperament of Rodents

- Conversely, rats born to high-grooming mothers, but reared by low-grooming mothers, become anxious adults and low-grooming parents.
- Thus, the transmission of these emotional and social traits is non-genetic, although without the intervention the traits would have seemed entirely genetically based.

A Sensitive Period for Shaping the Temperament of Rodents

- A salient example of the effects of early experience on brain biochemistry and gene expression is the influence of early mothering of young rats on the release of "stress hormones" (glucocorticoids), and the subsequent life-long change in the expression of genes for glucocorticoid receptors in key regions of the brain.
- In this example, early social interactions modify gene expression in a way that changes a critical set-point in a circuit that influences the animal's temperament throughout life.

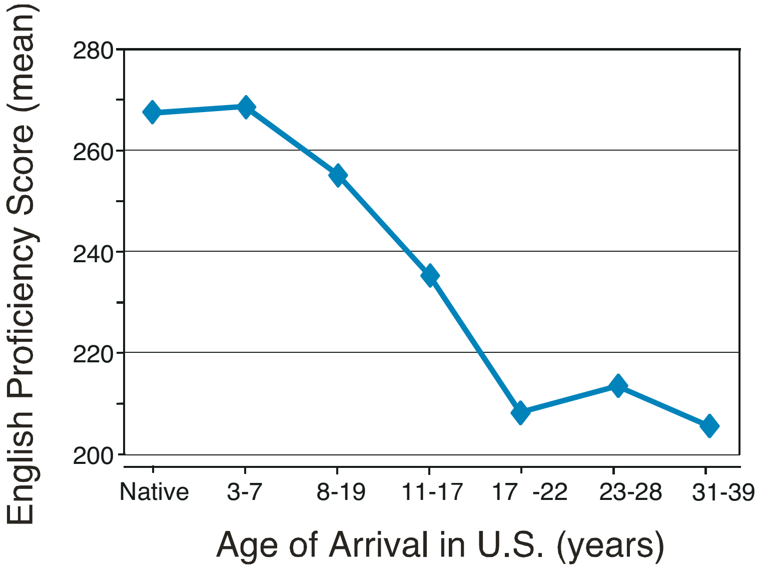
A Sensitive Period for Shaping the Temperament of Rodents

- Experiments such as these demonstrate that although genetics constrains the ranges of social and emotional characteristics that an individual rat can express, early experience can modify these characteristics over remarkably large extents.

Language

- Language is an example of a cognitive skill that is acquired readily in early life, but with great effort and never as thoroughly as an adult.
- The dependence of language learning on age holds for first languages and second languages, and for spoken languages as well as sign languages.

Second language learning



Early Experience Shapes Perceptual and Cognitive Abilities

- For most people, a thorough command of language is attained when learning occurs before about 7 years of age.
- Statistically, language proficiency decreases progressively as language learning is delayed beyond 7 years, and reaches adult levels by the end of adolescence.
- People who have never experienced language throughout their childhood are apparently incapable of acquiring a facility with language at a later age, despite intense training.

Early Experience Shapes Perceptual and Cognitive Abilities

- Not all aspects of language learning are subject to sensitive periods.
- For example, proficiency with phonetic comprehension and production, grammar and syntax is learned most effectively early in life, whereas semantics and vocabulary are learned with similar facility throughout life.
- Learning a second language as an adult requires far greater effort than learning it as a child, and the result is never as complete.

Why Experience During Circuit Maturation Is So Effective

- The Romanian infant studies support this notion.
- Romanian infants in orphanages received virtually no stimulation (intellectual or otherwise).
- The earlier the remediation, the better.

Anthropomorphic, developmental, and cognitive outcomes of Romanian and within-UK adoptees over time

	Within-UK adoptees	Romanian orphans		
Age of adoption (months):	6	Before 6	At 6–24	At 24–42
Weight at adoption	–	−2.1	−2.3	–
	–	(1.7)	(1.7)	–
Height at adoption	–	−1.8	−2.2	–
	–	(1.6)	(2.4)	–
Denver Developmental	–	76.5	48.1	–
Scale at adoption	–	(48.1)	(25.4)	–
Weight at age 4	0.45	−0.02	0.04	–
	(0.79)	(0.92)	(0.94)	–
Height at age 4	0.25	−0.29	−0.36	–
	(0.91)	(0.89)	(1.02)	–
Denver Developmental	117.7	115.7	96.7	–
Scale at age 4	(24.3)	(23.4)	(21.3)	–
McCarthy GCI at age 4	109.4	105.9	91.7	–
	(14.8)	(17.9)	(18.0)	–
Weight at age 6	0.30	0.02	−0.25	−0.85
	(0.90)	(0.97)	(0.96)	(0.98)
Percentage with	2	0	5	18
Denver Developmental	(1)	(0)	(2)	(7)
Scale at age 6 below 70				
McCarthy GCI at age 6	117	114	99	90
	(17.8)	(18.3)	(19.2)	(23.8)

Formulating and Estimating the Technology of Skill Formation

- A large body of research shows that early endowments and environment matter.
- But what happens later also matters.
- Remediation is costly.
- It is **not**, however, impossible, except when we get to very low levels of initial conditions.
- Resilience–"desistance"–is an important phenomenon.
- Need a framework to incorporate these insights.
- Basis for unifying the literature and conducting policy analysis.

Formulating and Estimating the Technology of Skill Formation

- Cunha and Heckman (2006) and Cunha, Heckman and Schennach (2006) build on the literature on intergenerational transmission of skills initiated by Becker and Tomes (1979, 1986).
- Becker and Tomes develop a one period model of childhood and focus on one “skill”.

Formulating and Estimating the Technology of Skill Formation

- We develop a multiperiod model of childhood investments in skills (early vs. late investments).
- We distinguish multiple skills (cognitive and noncognitive skills) with different technologies of investment and with feedback across the skills.
- Abilities are not just genetically determined but are the outcome of parental investment.

Formulating and Estimating the Technology of Skill Formation

- Todd and Wolpin (2003, 2005) present analyses of cognitive skill formation using test scores as outcome measures. We build on their work to:
  1. Also analyze noncognitive skills;
  2. Consider estimation of nonlinear technologies to capture substitution and remediation;
  3. Anchor test scores on outcomes: earnings and/or schooling choices. Test scores *per se* are arbitrary scales.

Formulating and Estimating the Technology of Skill Formation

- We embed the estimated technologies for the formation of skills in an overlapping generations model of Laitner (1992).
  1. Our framework allows us to discuss intergenerational transmissions of skills in a more general setting and with richer credit market settings than considered by Becker and Tomes.
  2. It allows us to discuss two distinct market failures — intragenerational versus intergenerational borrowing constraints — and to discuss the equity-efficiency trade-off or lack thereof in a more general setting.

Formulating and Estimating the Technology of Skill Formation

- We use this model for the analysis of optimal government policy of investments in human capital.

A Simple Introduction to The Technology of Skill Formation

Assume childhood lasts two periods “1” and “2”. This is contrary to a huge body of literature in economics and social policy that collapses childhood into a single period. Relaxing this assumption has important policy implications.

- Skills S are both cognitive and noncognitive.
- I_1 is investment in period “1”.
- I_2 is investment in period “2”.
- θ are environmental/genetic factors determined at birth.

A Simple Introduction to The Technology of Skill Formation

S_1 is the skill produced in period "1" according to:

$$S_1 = g\left(I_1; \theta\right)$$

S_2 is the skill produced in period "2" according to:

$$S_2 = k\left(S_1, I_2; \theta\right)$$

h is adult human capital,

$$h = S_2, \text{ a vector.}$$

Investments may be qualitatively different at different stages.

Self-Productivity and Complementarity

Universal Complementarity:

$$\frac{\partial^2 S_2}{\partial I_2 \partial S_1'} > 0$$

(Early Investment facilitates later investment.)
Can be true componentwise.

Example. Attainment of noncognitive skills through mother's warmth and encouragement raises effectiveness of both cognitive and noncognitive investments.

Self-Productivity and Complementarity

Self-Productivity:

$$\frac{\partial h}{\partial I_1} = \frac{\partial S_2}{\partial I_1} = \frac{\partial k}{\partial S_1}\frac{\partial S_1}{\partial I_1} > 0$$

(Early investment raises the stock of second period skills.)

Example. Those who attain higher first period skills are better able to progress to period two and produce skills more effectively.

- This explains the higher returns to education for more able individuals that is found in the literature.

Self-Productivity and Complementarity

To fix ideas, assume that we have one investment in each period. Two skills $S_2 = (S_2^C, S_2^N)$, cognitive and noncognitive.

We form the human capital that consists of cognitive and noncognitive components

$$h = h\left(S_1, S_2\right).$$

More generally, we can think of different tasks $T\left(S_1, S_2\right)$ using skills in different proportions.

Self-Productivity and Complementarity

We establish conditions under which we can express this as:

$$h = \left\{ \gamma I_1^{\phi} + (1-\gamma) I_2^{\phi} \right\}^{\frac{1}{\phi}}$$

- γ is a skill multiplier.
- γ is higher the greater the complementarity effect and the greater the self-productivity.
- ϕ is a measure of how well we can substitute late for early investments.

Simple Examples

- Example 1: Assume $\phi = 1$:

$$H = \gamma I_1 + (1 - \gamma) I_2$$

- This extreme case states that remediation is always possible. (However, it may not be cost effective.)
- This is at odds with the evidence from Neuroscience, Developmental Psychology and Economics.

Simple Examples (cont.)

- Example 2: Assume $\phi \to -\infty$:

$$H = \min\{I_1, I_2\}$$

- In this case, if investments in period one are very low, no remediation is possible.
- Adult human capital (and consequently adult success) is defined in the first periods of the life of an individual.

Critical and Sensitive Periods

- We have seen how early experience modifies the biochemistry and architecture of the brain.
- When this modification occurs during a limited time frame, it is called a sensitive period.
- When the modification occurs during a limited time frame and it is crucial for normal development, it is called a critical period.

Critical and Sensitive Periods (cont.)

- This technology is rich enough to capture the notions of Sensitive and Critical Periods in neuroscience.
- Period one is critical if $\gamma = 1$.
- Period one is sensitive if $0.5 < \gamma < 1$.

The Technology in an Intuitive Framework

- In the simplest set up, suppose that parents have $1 to invest in human capital.
- The problem is how to allocate this amount between early and late investments.
- This depends crucially on the parameters of the technology of skill formation.
- Let the price of the investment good be 1.
- Let r denote the interest rate.
- Suppose the parents seek to maximize the child's human capital.

The Technology in an Intuitive Framework

The problem of the parents may be written (adding a returns to scale parameter ρ, where $0 < \rho < 1$):

$$\max \left\{ \gamma I_1^{\phi} + (1-\gamma) I_2^{\phi} \right\}^{\frac{\rho}{\phi}}$$

subject to:

$$I_1 + \frac{1}{(1+r)} I_2 = 1$$

The Technology in an Intuitive Framework

Case 1: I_1 and I_2 are perfect substitutes $(\phi = 1) \Rightarrow$

$$S_2 = \gamma I_1 + (1 - \gamma) I_2$$

Corner solution. Concentrate investments early if and only if:

$$\gamma \geq (1 - \gamma)(1 + r)$$

Case 1 is what the current literature implicitly assumes.

The Technology in an Intuitive Framework

- It suggests that timing of investment is not an important issue. As a consequence, remediation is possible.
- However, even though it may be feasible to remediate, it may be very costly (especially if γ is close to 1).
- Even if it is technologically feasible to remediate, it is not necessarily economically feasible.
- May be more efficient to give the child a bond.

The Technology in an Intuitive Framework

Case 2: I_1 and I_2 are perfect complements ($\phi \to \infty$) $\Rightarrow$

$$S_2 = [\min \{I_1, I_2\}]^{\rho}$$

Then:

$$I_1 = I_2 = \frac{1+r}{2+r}$$

Complementarity has a dual face:

1. Early investments increase returns to late investments.
2. Late investments are needed to make early investments pay off.

In this case, timing of investments matter. In particular, no remediation is possible.

A poor initial environment cannot be offset.

The Technology in an Intuitive Framework

Case 3: $-\infty < \phi < 1$. A consequence of this model is:

$$\log\left(\frac{I_1}{I_2}\right) = \left(\frac{1}{1-\phi}\right)\log\left(\frac{\gamma}{1-\gamma}\right) - \left(\frac{1}{1-\phi}\right)\log\left(1+r\right).$$

- r increases $\Rightarrow \left(\frac{I_1}{I_2}\right)$ decreases;
  γ increases $\Rightarrow \left(\frac{I_1}{I_2}\right)$ increases
- The goal of our work is to understand the technology of skill formation and what the optimal profile of investments in skills are over time.

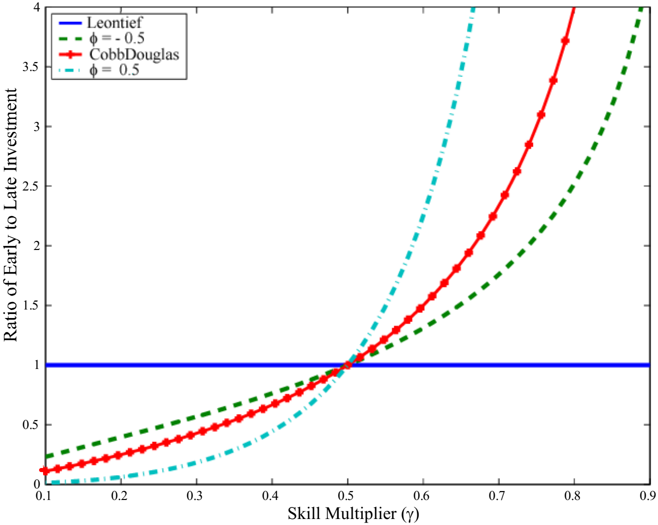
The Technology in an Intuitive Framework

- This technology is rich enough to capture the notions of Sensitive and Critical Periods in neuroscience.

$$h = \left[\gamma \left(I_1\right)^{\phi} + (1-\gamma)\left(I_2\right)^{\phi}\right]^{\frac{\rho}{\phi}}$$

- Period "1" is critical if $\gamma = 1$. Period "2" is critical if $\gamma = 0$.
- Period "1" is sensitive if $\gamma \geq 1-\gamma \Longrightarrow \gamma \geq \frac{1}{2}$.
- We develop more general models in Cunha, Heckman and Schennach (2006).

Ratio of early to late investment in human capital as a function of the skill multiplier for different values of complementarity



Our Approach

- We want to understand how the skills of the children evolve in response to:
  1. The stock of skills children have already accumulated.
  2. The investments made by the parents.
  3. The stock of skills accumulated by the parents themselves.

Our Approach

- C_t is the stock of cognitive skill of the child at age t.
- N_t is the stock of noncognitive skill of the child at age t.
- It is the parental investment at age t.
- C_M is mother's cognitive skill.
- N_M is mother's non-cognitive skill.

Our Approach

We estimate two equations:

- One technology for the production of cognitive skills:

$$C_{t+1} = F_{C,t}(N_t, C_t, I_t, C_M, N_M)$$

- One technology for the production of non-cognitive skills:

$$N_{t+1} = F_{N,t}(N_t, C_t, I_t, C_M, N_M)$$

Our Approach

- All of the variables are unobserved.
- However, from a rich array of panel data sets on child development and family resources, we have numerous proxies for each variable.

Our Approach

- We develop dynamic factor models that allow for nonlinearities (Cunha, Heckman, Schennach, 2006).
- This recognizes the proxy nature of the measurements and this turns out to be empirically important as there is a lot of measurement error.
- Allows us to combine numerous measurements into low dimensional indices.
- We anchor test scores so our estimates are based on an interpretable metric (e.g., earnings and schooling).

Econometric Work

- In a series of papers, we have estimated the technology of skill formation.
- We develop a dynamic factor model that allows us to use multiple inputs in a technology.
- Technology has elasticities of substitution below 1 (Cobb-Douglas).
- We are especially interested in the elasticity of intertemporal substitution parameters.
- It governs the early-late trade-off of investment.

Nonlinear model, time invariant technologies, two investment factors: noncognitive skills

$$\theta_{t+1}^{N} = \underset{(0.0484)}{1.4226}$$

$$\times \left(\begin{array}{ll} \underset{(0.0359)}{0.740} \left(\theta_t^N\right)^{-0.123} + & \underset{(0.0234)}{0.052} \left(\theta_t^C\right)^{-0.123} + \\ \\ \underset{(0.0302)}{0.126} \left(I_{1,t}\right)^{-0.123} + & \underset{(0.0178)}{0.015} \left(\theta_P^C\right)^{-0.123} \\ \\ +\underset{(0.0269)}{0.067} \left(\theta_P^N\right)^{-0.123} & \end{array} \right)^{\frac{1}{-0.123}}$$

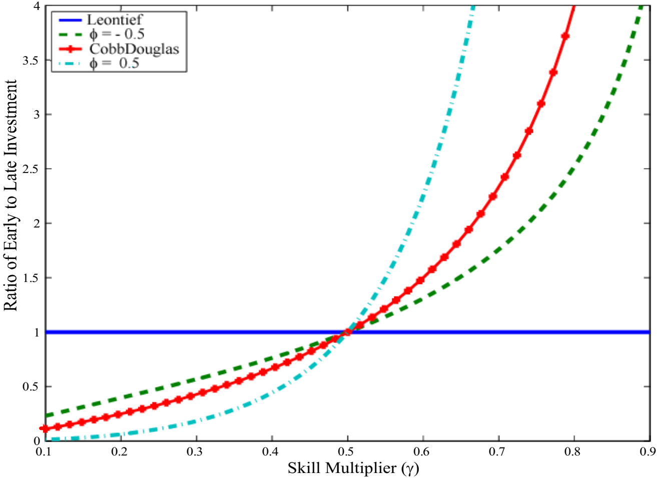
$$\sigma^N = \frac{1}{1 + .123} \doteq .9$$

Nonlinear model, time invariant technologies, two investment factors: cognitive skills

$$\theta_{t+1}^{C} = \underset{(0.0932)}{0.9842} \times \left(\begin{array}{ll} \underset{(0.0133)}{0.0455} \left(\theta_t^N\right)^{-0.254} + & \underset{(0.0581)}{0.7206} \left(\theta_t^C\right)^{-0.254} + \\ \underset{(0.0384)}{0.1168} \left(I_{1,t}\right)^{-0.254} + & \underset{(0.0265)}{0.0724} \left(\theta_P^C\right)^{-0.254} \\ +\underset{(0.0153)}{0.0446} \left(\theta_P^N\right)^{-0.254} & \end{array} \right)^{\frac{1}{-0.254}}$$

$$\sigma^C = \frac{1}{1+.25} \doteq .8$$

The ratio of early to late investment in human capital as a function of the skill multiplier for different values of complementarity



- We find much stronger yields of investment in the early years.

Illustration of the Results of Our Empirical Analysis

- Consider the following target group.
- Children who are 6 years old, who come from a very disadvantaged background.
- They are at the bottom 10th percentile in the distribution of skills.
- They receive investments that are at the bottom 10th percentile in the distribution of investments.
- Mother's are also at 10th percentile in the distribution of skills.

Comparison of Different Investment Strategies

Disadvantaged Children: First Decile in the Distribution of Cognitive and Non-Cognitive Skills at Age 6

Mothers are in First Decile in the Distribution of Cognitive and Non-Cognitive Skills at Ages 14-21

	Baseline	Changing initial conditions: moving children to the 4th decile of distribution of skills only through early Investment	Adolescent intervention: moving investments at last transition from 1st to 9th decile
High School Graduation	0.4109	0.6579	0.6391
Enrollment in College	0.0448	0.1264	0.1165
Conviction	0.2276	0.1710	0.1773
Probation	0.2152	0.1487	0.1562
Welfare	0.1767	0.0905	0.0968

Source: Cunha and Heckman (2006)

Comparison of Different Investment Strategies

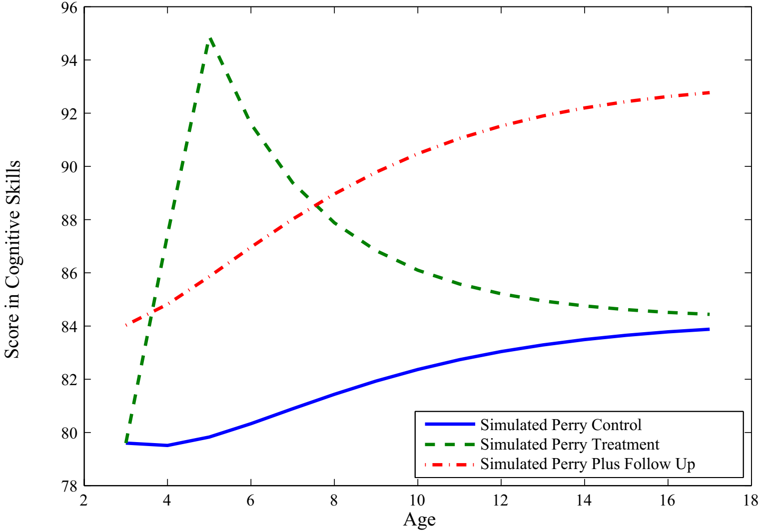
Disadvantaged Children: First Decile in the Distribution of Cognitive and Non-Cognitive Skills at Age 6

Mothers are in First Decile in the Distribution of Cognitive and Non-Cognitive Skills at Ages 14-21

	Baseline	Changing initial conditions: moving children to the 4^{th} decile of distribution of skills	Changing initial conditions and performing adolescent intervention	Changing initial conditions and performing a balanced intervention
High School Graduation	0.4109	0.6579	0.8477	0.9135
Enrollment in College	0.0448	0.1264	0.2724	0.3755
Conviction	0.2276	0.1710	0.1272	0.1083
Probation	0.2152	0.1487	0.1009	0.0815
Welfare	0.1767	0.0905	0.0415	0.0259

Source: Cunha and Heckman (2006)

Using the estimated technology to simulate balanced interventions

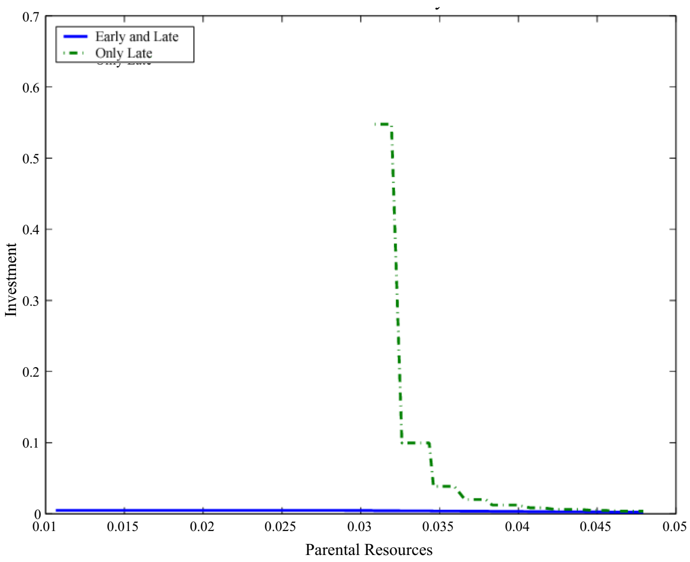


- The evidence strongly supports the economic efficiency of early initial investment that is sustained.
- Optimal distribution of investment:
  - Invest early? Yes.
  - But must be followed up to be effective.
- This is a consequence of dynamic complementarity.
- Later remediation is possible but to attain what is accomplished by early investment is much more costly (35–50%).
- If we start at too low a level, later skill investment is economically inefficient.

This model is embedded in an Aiyagari/Laitner economy

- We extend the analysis to account for
  1. Idiosyncratic uncertainty,
  2. Lifetime liquidity constraints (i.e., parents cannot leave debts to their children).
- Using these tools we develop optimal life cycle policies.
- We seek to determine the costs of delay in providing enriched early environments. Specifically we show the costs of remediation of adverse early environments.
- If early investment is sufficiently small, there is no economically efficient compensatory later investment.
- Better to give the child a bond or a bank account.

The cost of remediation of late vs. early and late interventions



The cost of remediation of late vs. early and late interventions

This figure is from Cunha and Heckman (2004), and is based on estimates reported above: $\rho = 0.7012$, $\gamma = 0.8649$, and $\phi = -0.4108$, shows the costs of remediation when the government makes up for parental deficits in investments due to binding lifetime credit constraints. Formally, the young parents solve $V_1(h, b, \varepsilon) = \max\{u(c_y) + \beta E[V_2(h, s, I_1, \eta)|\varepsilon]\}$, subject to the young budget constraint $c_y + I_1 + \frac{s}{1+r} = wh\varepsilon + b$, and the natural borrowing limit $s \geq -wh\eta_{\min}$. When old, the parents solve $V_2(h, s, I_1, \eta) = \max\{u(c_o) + \beta E[V_2(h', b', \varepsilon')|\eta]\}$, subject to the budget constraint when old, $c_o + I_2 + \frac{b'}{1+r} = wh\eta + s$; the constraint that prevents parents from extracting resources from their children, $b' \geq 0$; and the technology of skill formation. This figure plots the remediation costs for parents that receive no bequest in risk-free bonds, so that $b = 0$. The goal is to calculate the short-run costs of implementing a policy that attains the counterfactual human capital stock of the child if parents had access to full insurance against realizations of idiosyncratic shocks. There are two ways the government can pursue this policy. In the first case, the government provides educational goods and services in both early and late investment periods. In the second case, the government intervenes only during the late investment period. The message is clear: when the government intervenes only in the late period, remediation costs are much higher than when the government acts in both periods for all levels of parental income. Furthermore, for parents with very low income, there is no amount of government-provided educational goods and services that can attain the objective of the policy. In this figure, it is assumed that the government policy is unexpected when parents allocate resources to investments. See Cunha (2004) for long-run effects of government remediation policies.

Summary

- Evidence from human and animal studies shows the existence of critical and sensitive periods.
- These demonstrate the importance of early interventions.
- We formalize the literature on development in animal and human populations.
- Estimate the technology on human populations.
- We find evidence of critical and sensitive periods.
- These come earlier for cognitive traits; later for noncognitive traits.
- Associated with slower development of prefrontal cortex.

Summary

- Noncognitive traits stimulate production of cognitive traits (cross complementarity) but not vice versa.
- Elasticity of substitution over time greater for investments in noncognitive skills than for cognitive skills.
- This accords with evidence from animal studies.
- Later investment (associated with resilience) is possible but less efficient — consistent with the evidence from Neuroscience.
- Later investment is more efficient if early investment is made.
- Balanced portfolio weighted toward the early years is optimal.