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The Life-Cycle Research Productivity of Mathematicians and Scientists[1]

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Declining research productivity with age is implied by economic models of life-cycle human capital investment but is denied by some recent empirical studies. The purpose of the present study is to provide new evidence on whether a scientist's output generally declines with advancing age. A longitudinal data set has been compiled for scientists and mathematicians at six major departments, including data on age, salaries, annual citations (stock of human capital), citations to current output (flow of human capital), and quantity of current output measured both in number of articles and in number of pages. Analysis of the data indicates that salaries peak from the early to mid-60s, whereas annual citations appear to peak from age 39 to 89 for different departments with a mean age of 59 for the 6 departments. The quantity and quality of current research output appear to decline continuously with age.

Key Words: Citations, Longitudinal, Age, Academics, Chemists, Physicists, Economists, Mathematicians, Achievement, Human capital

COLE and others have recently presented evidence (Cole, 1979; McDowell, 1982; Stern, 1978; Zuckerman, 1977) in defense of the surprising thesis that a scientist's productivity does not vary with age. The finding conflicts with accepted wisdom and with an earlier literature epitomized by Lehman's *Age and Achievement,* that had found that scientists' productivity often reached a peak relatively early in life and then declined steadily and significantly. Some recent research also supports Lehman's general findings (Eagly, 1974; Simonton, 1984). The issue may be of more than simply intellectual interest because Cole intends to address policy makers concerned with the prospect that the increasing average age of scientists over the next 20 years will reduce the country's "scientific capacity" (1979, pp. 959–977).

No less surprised than others by Cole's findings are those economists whose human capital models (Becker, 1974; Diamond, 1984) imply that as the end of life approaches, the stock of human capital, and hence productivity, declines because no new investment offsets depreciation. Writing a research paper can be interpreted as investment in human capital (Weiss & Lillard, 1982), specifically as investment in knowledge at the frontiers of the discipline. Such human capital, especially at major research graduate universities, increases a scientist's productivity in the activities directly demanded by the university such as teaching, fund-raising, administration, and the gate-keeping activity of peer review. Life-cycle human capital investment models imply that as a scientist ages, his investment in human capital will decline for two reasons. One is that fewer periods remain in which additional human capital will be available. The other is that as a scientist ages his stock of human capital increases, thereby increasing the productivity of his time in nonresearch activity. In fact, evidence from a time use survey indicates that research time diminishes with age (Harmon, 1965). Time spent in administration increases with age but time spent in teaching decreases. The latter finding might be consistent with the life-cycle investment account just sketched if productivity in both administration and teaching increased with age, but the increase was enough greater in administration to result in an allocation of time away from teaching and into administration.

Related to the implication of life-cycle models that investment in human capital will decline with age is the implication that for a period of time the stock of human capital will be increasing even though the annual flow of investment in human capital is declining. This would occur so long as the

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annual investment remains greater than the annual loss of human capital due to depreciation. The models assume that annual salary is equal to the stock of human capital multiplied times a constant annual rate of return to human capital. Under such an assumption the models imply that the life-cycle salary profile will have the same shape as the profile for the stock of human capital. Although recent models of implicit contracts (e.g., Freeman, 1977; Harris & Holmstrom, 1982) reject the assumption of the life-cycle model that workers are paid in each period the value of their marginal product, the models published so far have yielded no new implications for the optimal life-cycle pattern of human capital investment. In fact the human capital implications of implicit contracts models can be quite similar to those of the standard life-cycle models.

Data and Methodology

Because the purpose of the study was to investigate the productivity of research scientists, a population with a high concentration of research scientists was chosen: academics who eventually became full professors in highly ranked departments. The University of California at Berkeley and the University of Illinois at Urbana were chosen from among the highly ranked departments because they, as state supported schools, make faculty salary data publicly available. At Berkeley salary data were obtained eventually from the Office of Academic Personnel. At Illinois salary data were readily available going back at least to 1945 in the form of printed annual reports by the Board of Trustees. School year salary data were coded as applying to the first of the two relevant years. So, a salary for the 1970–1971 school year was coded as the salary for 1970. The nominal salary data were transformed into 1984 dollars using the Consumer Price Index. In order to insure the robustness of the results and to allow interdepartmental comparisons, three departments at each school were chosen for study: mathematics, physics, and economics at Berkeley and mathematics, physics, and chemistry at Illinois. All of these six departments have ranked in the top 15 in their respective fields over the period 1925–1977 ("How Professors Rated," 1979; Keniston, 1959; Roose & Andersen, 1970).

The basic samples were obtained from faculty listings in catalogs from the late 1970s. Because these listings underrepresented those who were nearing the end of their careers in the early years of the *Science Citation Index* (i.e., the 1960s) the samples were augmented by the addition of all those full and emeriti professors listed in a catalog from the middle 1960s who were not listed in the catalog from the late 1970s. From these samples, any scientist was dropped for whom biographical information was not available in either *American Men and Women of Science* or the directory of members of the American Economic Association. Occasionally a scientist also was omitted from the sample if his name was identical to another scientist's as listed in the *Science Citation Index* because it would have been too costly to distinguish citations to his work from those to the like-name scientist's work. Salary data necessarily extend only up to the age of retirement. Citation and publication data, however, were included through the age of 80 for the older members of the sample. Summary statistics for the whole sample are provided in Table 1.

Volumes of the *Science Citation Index* have been published annually since 1961, but because the coverage of math journals in the first 4 years was very limited, only the years 1965–1979 were used to obtain mathematics citations counts. For economics, the *Social Science Citation Index* from 1966–1979 was used to obtain citation counts. The measure of citations used in the study is simply the total number of citations made in a year to all of a scientist's earlier work. For example, since E. Spanier was cited 40 times in 1979 according to the 1979 *Index*, Spanier's 1979 citation count would be 40.

As measures of quality, citation counts from the *Science Citation Index* have been criticized on several grounds. A vain scientist who cites himself frequently, for instance, would be judged on the basis of the citation measure to be a better scientist than the otherwise identical, but modest scientist who cites himself infrequently. Perhaps a better

Table 1. Descriptive Statistics on Pooled Sample of Data from All Six Departments

Variable	Number of observations	*M*	*SD*
Citations received per year to all of the person's previous work	4,691	37	74
Year of birth	4,691	1924	11
Year of PhD	4,691	1951	11
Salary in 1984 $	3,815	54,667	15,208

Note. An observation represents data on a given scientist in a given year. So if 10 years of data are available for a scientist, then that scientist will account for 10 observations in the sample.

known (Diamond, 1985, 1986) and more important defect of the *Science Citation Index,* however, is that it only lists citations under the first author of a multiple-authored article. In order to learn the seriousness of this defect full citation counts were constructed for 48 Berkeley mathematicians in a study reported more fully elsewhere (Diamond, 1986). Surprisingly, when such full citation counts were entered in an earnings function, they had less explanatory power (as measured by *t* statistics) than first author citation counts. Although based on a single small sample, the results suggest that first author citation counts may be a useful proxy for full citation counts for some purposes.

For Berkeley mathematicians a second citation count was computed that was intended to measure the quality of current output. It consists of the sum of the citations received by a year's output in the 3 years following a 1-year lag. So, for instance, if E. Spanier's 1965 publications had been cited three times in 1967, seven times in 1968, and four times in 1969, the citations to his 1965 output would be measured as 14. The year lag is introduced in order to allow time for the publications to become known and for other articles to be published that can take them into account. In principle, it would be better to follow the citation history of an article for longer than 3 years. But because there are only 15 years of citations and because each year's publications must be followed for a comparable length of time, any increase in the number of years for which citations are counted would reduce the number of years of publication that could be compared. The last year of publication that was included was 1975.

The measure of quality used here does not capture all the dimensions of quality that may be of interest. In particular, data limitations do not permit us to observe the durability of a paper's contribution or, a fortiori, a paper that is "ahead of its time." I hypothesize, however, on the basis of experience in collecting several citation data sets that a very high percent (more than 99%?) of articles that are ever highly cited were already highly cited within 3 years after publication. Unfortunately, I do not know of any rigorous tests of this hypothesis. The closer the hypothesis is to the truth, the better the just-discussed citation count is as a measure of quality.

Life-cycle profiles for salaries and research productivity were inferred from the coefficients on age and age-squared in ordinary least squares regressions that controlled for period and cohort effects by the inclusion of appropriate dummy variables. One important motivation for the inclusion of period dummies in the salary regressions was to control for possible changes over time in the demand for scientists.

Heckman and Robb in unpublished work have shown that even for longitudinal data a regression that incorporates age, period, and cohort effects is underidentified if the cohort variable is defined as the scientist's year of birth. We avoid strict multicollinearity by defining the cohort variable as year of PhD. But because year of PhD is expected to be highly collinear with year of birth, we still expect identification to be a problem. As a solution to the problem, Heckman and Robb suggest replacing either period or cohort variables with more sharply focused behavioral variables. Unfortunately, for our data set no good behavioral variables exist that pick up the kinds of effects intended by the period and cohort variables. To proceed with estimation of the effect of age, either the cohort effect must be normalized to zero (following Johnson & Stafford, 1974) or the period effect must be normalized to zero (following Weiss & Lillard, 1978). We estimated all regressions using both normalizations and found that the qualitative results for age were robust. Due to space constraints only the results are reported for the (randomly chosen) normalization where the cohort effects are set equal to zero.

Although some studies have shown unobserved fixed (or person) effects to be statistically significant in determining earnings, we do not control for them here. The potential problem in not controlling for unobserved person effects can be illustrated by a hypothetical example. Intelligence, for instance, would presumably influence earnings but is not directly observed in our sample. If intelligence was correlated with some included variable, say cohort (on the assumption that older cohorts differ in intelligence from younger cohorts), then the estimated coefficients on the cohort dummy variables would be biased.

If a person is observed for more than one period, as with longitudinal data, then person effects can be controlled in principle by using a "fixed effects model" that either includes person specific dummy variables as independent variables or else uses the equivalent technique of first differencing all dependent and independent variables. The main justification for not controlling for person effects here is that, given our data, the tractability of a fixed effects model is greatly reduced due to differences in the number of observations for each scientist. The lack of control for person effects will not bias the estimates of the observed variables if the standard assumption is true that the observed variables are uncorrelated with the unobserved person effects (Rosen & Taubman, 1982).

An *F* test was performed to test the null hypothesis that the Berkeley mathematics sample was from the same population as the Illinois mathematics sample. The null hypothesis was rejected at the .05 level so separate regressions are reported for each sample. The same test was performed, and the null hypothesis likewise rejected, for the Berkeley physics and Illinois physics samples.

RESULTS

Although earlier salary studies of academics occasionally had used crude (Katz, 1973; Koch & Chizmar, 1973; Siegfried & White, 1973) measures of quality of research as an explanatory variable, the first study to use citations for this purpose was a 1970 *Journal of Business* paper by Holtmann and Bayer (1970). In an earnings regression including as explanatory variables experience, IQ, rank, field, as well as others, the authors found for a cross-section of 3,495 PhDs in the natural sciences that a citation explanatory variable was positive and significant at the .001 level (sic). More recently, Hamermesh, Johnson, and Weisbrod (1982) have estimated salary regressions on citations and experience for a sample of 122 Midwestern full professors of economics. They found that the coefficient on citations was always positive and usually significant whereas that on citations-squared was usually negative and usually not significant. They also found that the coefficients on experience and experience-squared, though usually of the "right" sign, were never significant. This latter surprising finding is no doubt because the standard deviation for experience in their samples was small: ranging from .76 years in the pooled sample up to 2.06 years for their school number 5.

When regressions similar to those in the Hamermesh et al. study were estimated for the data in the present study (Diamond, 1986) the coefficients on citations were always positive and almost always significant whereas the coefficients on citations-squared were always negative and almost always significant. The results support the expectation that over the observed levels of citations, the marginal value of a citation is almost always positive and diminishing.

The life-cycle human capital investment models discussed earlier imply that with increasing age the stock of human capital and, hence, the level of salaries, will rise for a period of time and then eventually decline. The models make no specific prediction about the age at which the age-citation and age-salary profiles will peak, however, only saying that the age at the peak will depend on such factors as the rate of depreciation of human capital and the rate of return to human capital. The regression results reported in Table 2 are all consistent with the implication that the age-citation and age-salary profiles are concave downward, that is, that the citation stock and salaries rise, peak, and then fall. The peak ages implied by the regressions in Table 2 are reported in the first 12 rows of Table 4. Note that real salaries consistently peak in the early to mid 60s while the peak age for annual citations ranges from 39 for Berkeley physicists to 89 for Illinois mathematicians. The mean peak age for the citation stock for the 6 samples is 59. If productivity in nonresearch activities such as teaching and administration depends on the stock of human capital as measured by annual citations, then the evi-

Table 2. Log-Salary and Citation Regressions on Age

Regression Number	1	2	3	4	5	6	7	8	9	10	11	12
University	Berkeley	Berkeley	Berkeley	Berkeley	Berkeley	Berkeley	Illinois	Illinois	Illinois	Illinois	Illinois	Illinois
Field	Math	Math	Physics	Physics	Econ	Econ	Math	Math	Physics	Physics	Chem	Chem
Dependent variable	Ln Sal	Citations	Ln Sal	Citations	Ln Sal	Citations	Ln Sal	Citations	Ln Sal	Citations	Ln Sal	Citations
Coefficient	.066	2.256	.087	1.336	.060	2.342	.098	1.244	.036	2.167	.120	13.661
on age	(10.554)	(4.069)	(13.536)	(.957)	(11.414)	(3.092)	(15.928)	(2.458)	(5.089)	(.877)	(14.479)	(6.632)
Coefficient on	−.0005	−.018	−.0007	−.017	−.0005	−.021	−.0008	−.007	−.0003	−.022	−.0010	−.116
age squared	(−7.782)	(−3.195)	(−10.675)	(−1.138)	(−8.767)	(−2.923)	(−12.837)	(−1.420)	(−4.368)	(−.909)	(−11.418)	(−5.594)
Number of observations	622	728	830	1112	300	394	731	857	953	1073	379	527
Number of scientists	51	51	60	60	30	30	59	59	69	69	28	28
R^2	.52	.11	.51	.03	.61	.08	.56	.07	.13	.01	.70	.16

Note. *t* statistics are reported in parentheses. Period effects were controlled in all of the regressions by the inclusion of dummy variables for the range of years in which the observation falls. The coefficients on the dummy variables are not reported here due to space constraints and because of ambiguity in their interpretation (see discussion of identification on the previous page).

Table 3. The Impact of Age on the Quantity and Quality of Current Output for Berkeley Mathematicians

Dependent variable	Regression Number			
	1 Articles per year	2 Cites per article	3 Pages per year	4 Cites per page
Age	−.017	−0.75	−.314	−.003
	(−4.423)	(−2.231)	(−3.921)	(−1.899)
Period 2[a] (1968–1971)	.549	−.115	9.075	−.0002
	(5.108)	(−.118)	(4.066)	(−.005)
Period 3 (1972–1975)	.537	.474	10.193	.0007
	(5.048)	(.476)	(4.613)	(.015)
Constant	1.292	7.554	21.970	.317
	(6.677)	(4.885)	(5.466)	(4.506)
Number of observations	665	276	665	276
Number of mathematicians	45	45	45	45
R^2	.09	.02	.07	.01

Note. *t* statistics are reported in parenthesis.
[a]The omitted period is 1965–1967.

Table 4. Peak Ages and Changes with Age in Quantity and Quality of Current Output, Total Citations Per Year, and Log of Real Salary

Sample	Peak age	Predicted value of dependent variable at age 30	50	70
Berkeley mathematics				
Salary	66	39,932.42	67,167.45	75,731.10
Annual citations	62	7.25	23.57	25.49
Berkeley physics				
Salary	62	32,759.36	60,897.30	64,662.97
Annual citations	39	13.30	12.80	−1.30
Berkeley economics				
Salary	60	44,176.32	77,338.28	98,316.22
Annual citations	56	8.19	21.43	17.87
Urbana mathematics				
Salary	61	33,387.75	65,903.33	68,592.88
Annual citations	89	1.50	15.18	21.86
Urbana physics				
Salary	60	39,773.02	50,561.43	50,561.43
Annual citations	49	22.62	30.76	21.30
Urbana chemistry				
Salary	60	31,192.85	69,420.97	69,420.97
Annual citations	59	−2.50	85.07	79.94
Berkeley mathematics				
Articles per year	27[a]	.78	.44	.10
Citations per article	27[a]	5.30	3.80	2.30
Pages per year	27[a]	12.55	6.27	−.01
Citations per page	27[a]	.23	.17	.11

[a]Because the quantity and quality of current output appear to be monotonically decreasing functions of age, the peak is the first age, which for the purposes of this table is taken to be the mean age of receipt of PhD (i.e., 27).

dence suggests that productivity in those activities peaks at a fairly late age.

Annual research productivity, however, should decline continuously with age if we are right in interpreting such productivity as investment in human capital. For the Berkeley mathematicians we obtained measures, described earlier, of the quantity and quality of a mathematician's current output. The effect of age on these measures is reported in Table 3. In initially estimated regressions age-squared terms were included, but the coefficients on such terms were never statistically significant. This result, along with the negative coefficients on age in the regressions in Table 3, suggests that the quantity and quality of current output declines monotonically with age.

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