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THE INTERACTION BETWEEN CAPITAL INVESTMENT AND R&D IN SCIENCE-BASED FIRMS

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ABSTRACT

This paper analyzes the interaction among R&D, capital investment, and the stock market rate of return for 191 firms in science-based industries for the period 1973-1981. Using a framework based on dynamic factor analysis, we show how several prominent hypotheses about the determination of R&D and investment generate testable parameter restrictions. The data indicate that R&D Granger-causes investment, but that investment does not Granger-cause R&D. We use this finding to examine the validity of those hypotheses, to characterize the movements over time of R&D and investment, and to measure the stock market valuation of these movements.

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This paper investigates empirically the interaction among research and development (R&D), capital investment, and the stock market performance at the firm level in science-based industries. In the literature on technical change there are three prominent, and very different, hypotheses concerning the determination of R&D and investment expenditures. The first, which we call the "symmetry" hypothesis, is essentially an extension of neoclassical investment theory based on costs of adjustment to multiple capital assets. This theory treats the stocks of physical capital and knowledge symmetrically, and the flows of investment and R&D as gross increments to these stocks (For discussion see Griliches (1979), and Nadiri and Rosen (1973)). The remaining two hypotheses treat R&D and investment asymmetrically. Rosenberg (1974), Schumpeter (1950) and others have argued that the returns to R&D effort and hence the R&D decision depend both on the ability of the firm to transform R&D inputs into economically useful output (technological opportunity) and on its ability to extract the associated monetary benefits (market size and the degree of appropriability). Therefore, while product demand and factor prices affect all input decisions, including capital investment and R&D, the R&D decision also depends on technological opportunity and appropriability. We refer to this approach as the "technological opportunity" hypothesis. The third hypothesis is based on the argument that implementation and commercialization of the new ideas generated by R&D require additional capital investment by the firm. This model stresses that the output of the R&D process, and not simply R&D input, drives the investment. When research capabilities are known by the firm, the basic implication of this "inducement" hypothesis is that capital investment depends on some indicator of the success of the R&D process, in addition to the factors that determine R&D expenditures (see Lach (1986)).

There is a basic stylized fact about R&D and investment which any of these models must explain. The sample used in this paper covers 191 firms in science-based industries for the period 1973-1981. The sample variance in the growth rate of investment is four times as large as the variance in the growth rate of R&D. For only seven of the 191 firms is the ranking of these variances reversed. This conclusion also holds for the (log) levels and has been observed in other samples (see Mairesse and Siu (1984)). Since R&D moves more smoothly over time than investment, the neoclassical model of investment is compelled to rationalize this empirical fact by finding that R&D is subject to more severe costs of adjustment than capital investment. This conclusion seems implausible since the bulk of R&D expenditures consists of labor expenses for scientists, engineers and auxiliary staff. The other two hypotheses are more flexible because their explanation of the stylized fact can be based not only on different response parameters to common determinants, but also on the possibility that R&D and investment are determined by different factors.

In this paper we develop a general framework to analyze the determination of R&D and investment which can be used to distinguish empirically among the preceding hypotheses. The model, which is adapted from Pakes (1985), is based on dynamic optimization by the firm in an uncertain environment. There are three endogenous variables, R&D, investment, and the stock market rate of return of the firm. These variables are determined by the evolution of three unobservable stochastic factors which are used to characterize the uncertain environment. The basic model has the form of a dynamic factor analysis (see Geweke (1977) and Sargent and Sims (1977)). We show that each of the aforementioned hypotheses can be framed in terms of a specific pattern of zero loadings in the dynamic factor structure. The model has an equivalent representation as a vector autoregression in which tests of these hypotheses take the form of parametric exclusion restrictions, which can be interpreted as particular Granger causal orderings among the endogenous variables.

Section 1 presents the model and describes the different hypotheses concerning the determination of R&D and investment, and their implications for parameter restrictions on the model. Section 2 describes the data and presents the results of the statistical tests of these implied restrictions. In Sections 3 and 4 we present and discuss the empirical results for the restricted model supported by the tests in Section 2. The discussion is focused on the implications of the response parameters of R&D and investment to the unobservable stochastic factors, and on the interpretation of the stochastic factors themselves. Concluding remarks close the paper.

1. Statement of the Model

Consider a firm with an infinite discrete time horizon which is engaged in three types of activities: research and development (R&D), investment in capital goods, and production and marketing of its output. Assume that all inputs required by these activities are chosen so as to maximize the expected discounted value of their net cash flows. The expectation is taken conditional on the information set available to the firm at every period t, say Ω_t. Ω_t includes past values of expenditures on all inputs, as well as all economic and technological information known to the firm in period t that can be used in forecasting the distributions of future net cash flows (current and past determinants of demand, factor prices, technological opportunities, etc.). Assume furthermore that all inputs, except for those in R&D and investment activities, can be adjusted costlessly at the beginning of each period. It follows that at every t, expenditures on these inputs are set to maximize current profits, given Ω_t and the expenditures on R&D and investment for that period, R_t and I_t. Let these "operating" profits be denoted by $\pi(R_t, I_t, \Omega_t)$. An R&D and investment program consists of a sequence of random variables representing current and future R&D and investment expenditures, $\{R,I\}_t \equiv \{R_{t+\tau}, I_{t+\tau}\}$, $\tau=0,1,2,\ldots$. The expected discounted value of an arbitrary policy can be written as

$$(1) \qquad W(\{R,I\}_t, \Omega_t) = E\{\sum_{t=0}^{\infty} d^{\tau}[\pi(R_{t+\tau}, I_{t+\tau}, \Omega_{t+\tau}) - C(R_{t+\tau}, I_{t+\tau}, \Omega_{t+\tau})]/\Omega_t\}$$

where d is the discount factor, and $C(\cdot)$ is the cost associated with expenditures on R&D and investment. Except for stationarity and the standard regularity conditions required for this type of dynamic programming problem (Lucas and Prescott (1971)), this formulation imposes no special restrictions on the form of the profit function $\pi(\cdot)$ or on the cost of adjustment function $C(\cdot)$.

Formally, our behavioral assumption is that if the firm chooses $\{R^*, I^*\}_t$, then

$$(2) \qquad V(\Omega_t) \equiv \max_{\{R,I\}_t} W(\{R,I\}_t, \Omega_t) = W(\{R^*, I^*\}_t, \Omega_t).$$

The optimal policy is a sequence of random variables whose realized value at time $t+\tau$ is determined by the realization of $\Omega_{t+\tau}$. Thus, optimal R&D and investment expenditures at time t depend on their own past values $\{R_{t-1}, I_{t-1}, \ldots\}$ as well as on the economic and technological information known to the firm at time t, denoted by $\bar{\Omega}_t$. It is clear that through successive substitutions, one can obtain a reduced form expression for current optimal R&D and investment as a function of $\bar{\Omega}_t$,

$$(3) \qquad \begin{aligned} R_t^* &= F(\bar{\Omega}_t) \\ I_t^* &= G(\bar{\Omega}_t) \end{aligned}$$

These are the policy functions which relate optimal R&D and capital investment to the economic and technological information available to the firm.

The data used in the empirical analysis consist of time series data for a cross-section of firms on R&D and investment expenditures, and on the stock market one-period excess rate of return on the firm's equity. The latter is computed as the rate of change of the value of a dollar share over the given period plus the corresponding dividend minus the interest rate, and is denoted by q_t. If the stock market evaluates the firm at its expected discounted value of net earnings and possesses the same information as the firm, q_t should equal the percentage change in the expected discounted value of the firm's net cash flows caused by the new information accumulated between t-1 and t (see Pakes (1985)),

$$(4) \qquad q_t = [V(\bar{\Omega}_t) - E\{V(\bar{\Omega}_t)/\bar{\Omega}_{t-1}\}]/V(\bar{\Omega}_t)$$

Equations (3) and (4) tell us that knowledge of the value and policy functions, $V(\cdot)$, $F(\cdot)$ and $G(\cdot)$, and of the stochastic properties of $\bar{\Omega}_t$ is required for the joint determination of the evolution over time of the firm's stock market rate of return, R&D and investment expenditures. To this end, suppose that $\bar{\Omega}_t$ can be decomposed into three exhaustive sets or random variables, $\bar{\Omega}_t = \{\{X_{1\tau}\}, \{X_{2\tau}\}, \{X_{3\tau}\}, \tau=\ldots t-1,t\}$.[1] $\{X_{i\tau}\}$ represents the history, say, of market size for the firm's output, or of factor prices, or of technological advances in the firm's R&D area of expertise. Using logarithmic approximations for V, F and G, and assuming that $\{x_{1t}=\log X_{1t},\ x_{2t}=\log X_{2t},\ x_{3t}=\log X_{3t}\}$ evolves as a covariance stationary stochastic process, equations (3) and (4) can be solved for $r_t = \log R^*_t$, $i_t=\log I^*_t$, and q_t to obtain,

$$
\begin{aligned}
r_t &= A_{11}(L)\epsilon_t + A_{12}(L)\eta_t + A_{13}(L)\mu_t \\
i_t &= A_{21}(L)\epsilon_t + A_{22}(L)\eta_t + A_{23}(L)\mu_t \qquad (5) \\
q_t &= A_{31}(L)\epsilon_t + A_{32}(L)\eta_t + A_{33}(L)\mu_t
\end{aligned}
$$

where $\{\epsilon_t,\eta_t,\mu_t\}$ are mutually uncorrelated white noise processes corresponding to the trivariate Wold representation of $\{x_{1t},x_{2t},x_{3t}\}$. $A_{ij}(L)$ is a polynomial in the lag operator L.[2,3] The realizations of the stochastic process $\{\epsilon_t,\eta_t,\mu_t\}$ drive the evolution over time of our three observed variables $\{r_t,i_t,q_t\}$. Estimation of the various lag operators in (5) and of the variances of the innovations or shocks will enable us to assess the quantitative importance and the time pattern of each individual shock in the observed movements of $\{r_t,i_t,q_t\}$.

So far, no interpretations or restrictions have been attached to the equations in (5). At this stage, the qualitative distinction between the shocks arises naturally from the restrictions to be imposed (and tested) on the parameters in (5). We first consider the restrictions on the q equation. Adopting the view that the stock market is "efficient" implies that current rates of return cannot be predicted using past information. This implies that only contemporaneous shocks should affect q. One can normalize these nonzero coefficients to unity; this affects the magnitude of the coefficients in (5) without altering their interpretation. Using this convention and under "stock market efficiency", the q equation reduces to

$$(6) \qquad q_t = \epsilon_t + \eta_t + \mu_t$$

There is some controversial evidence that the variance of stock prices is larger than the variance of the discounted value of expected earnings (see, for example, LeRoy and Porter (1980), and Shiller (1981). For criticism see Kleydon (1986)). This so-called "excess volatility" hypothesis cannot be tested in our model. However, we do allow for the empirical possibility that there are factors which affect the firm's stock market rate of return but do not affect either its R&D or capital investment decisions. This idea is incorporated into our model by letting μ be an idiosyncratic shock to q, which implies the testable restrictions $A_{13}(L) = A_{23}(L) = 0$. The interesting issue here is the comparison between the variance of μ, σ_μ^2, and the variance of the shocks affecting both R&D and investment, σ_ϵ^2 and σ_η^2.

Provisionally accepting these restrictions (test statistics are provided later), the model consists of equation (6) and

$$
(7) \quad \begin{aligned} r_t &= A_{11}(L)\epsilon_t + A_{12}(L)\eta_t \\ i_t &= A_{21}(L)\epsilon_t + A_{22}(L)\eta_t \end{aligned}
$$

Equations (7) provide a general representation of the interaction between R&D and investment, which we call the symmetry hypothesis. One prominent model in the literature on technical change which generates this structure is the production function approach. This treats R&D expenditures as increments to a stock of knowledge, analogous to investment as increments to a stock of physical capital, within the framework of a neoclassical production function subject to costs of adjustment. Since optimal adjustments in one stock are usually accompanied by adjustments in the other, this hypothesis implies that both ϵ and η are present in the R&D and investment equations.[4] Suppose, to the contrary, that η is not a determinant of R&D expenditures. Then, since it is uncorrelated with ϵ, movements in η will change investment without affecting R&D, thereby contradicting the hypothesis. The hypothesis implies that there must be nonzero coefficients in the lag polynomials of ϵ and η in each equation in (7).

Specific sets of parameter restrictions in equations (7) can be derived as implications of two very different hypotheses in the literature on technical change about the interaction between R&D and investment. The first is the technological opportunity hypothesis, according to which R&D expenditures react to factors other than purely economic ones, such as advances in basic science, methods and techniques. These factors are assumed not to affect investment expenditures directly, implying that either ϵ or η is absent in the investment equation in (7). Choosing η to represent the technological opportunity leads to the restriction: $A_{22}(L) = 0$ and $A_{12}(L) \neq 0$.

In addition to a common factor, R&D is affected by another shock which affects the stock market rate of return but <u>does not</u> affect investment.

The second hypothesis is based on the argument that some investment is required for the implementation and commercialization of new ideas (i.e., of the output of the R&D activity). Therefore, a firm's investment responds to an R&D "success" shock which represents the unpredictable output of the R&D process conditional on past R&D inputs. Provided that the R&D success shock does not convey useful information about the firm's R&D capabilities, it will not affect the optimal level of R&D expenditures (see Lach (1986)). Letting η represent the R&D success shock implies the restrictions $A_{12}(L) = 0$ and $A_{22}(L) \neq 0$. We call this the inducement hypothesis.

These hypotheses, as stated, are highly stylized and for this reason they generate very sharp parameter restrictions. Actually, much of the discussion in the literature on technological opportunity focuses on richer and more realistic versions in which advances in science and technology affect R&D first and then, through R&D and only with a lag (say θ), affect investment (for example, Rosenberg (1969, 1974), Griliches (1979)). The implication for the model in (7) is that $A_{22,\tau} = 0$ for $\tau < \theta$. Similarly, if one enriches the inducement hypothesis by allowing the firm to learn about its R&D capabilities from its R&D successes, with some lag ψ, then η's which are dated at least ψ periods earlier will also affect current R&D decisions. The implication for the model in (7) is that $A_{12,\tau} = 0$ for $\tau < \psi$. This paper focuses on the stylized versions of the hypothesis, but some remarks on the extended versions will also be made in the empirical section.

To test these hypotheses, the system in (5) has to be consistently estimated. To do so, let n be the index for firms, n=1,...,N and let m be the lag length and define $Z_{nt} = (r_{nt}, i_{nt}, q_{nt})'$, $V_{nt} = (\epsilon_{nt}, \eta_{nt}, \mu_{nt})'$, and $A(L)$ to be the (3×3) matrix of lag operators $A_{ij}(L)$, i,j=1,2,3. The system can then be written compactly as,

$$(8) \qquad Z_{nt} = A(L)V_{nt} \quad t = m+1,\ldots,T.$$

The autoregressive form of (8) is,

$$(9) \qquad Z_{nt} = B(L)Z_{nt-1} + CV_{nt} \qquad t = m+1,\ldots,T.$$

where C is a (3×3) matrix of constants and $B(L)$ is a (3×3) matrix of lag operators $B_{ij}(L)$, i,j=1,2,3.[5] Equation (9) is estimated using the N(T-m) available observations. It is assumed that $Cov(V_{nt}, V_{kt}) = 0$, for $n \neq k$.[6] The covariance matrix of the whole system is therefore block diagonal, the blocks being $C\Sigma C'$ where $\Sigma = diag[\sigma^2_\epsilon, \sigma^2_\eta, \sigma^2_\mu]$. Estimation of (9) by GLS yields consistent and efficient estimators.

The restrictions in system (5) discussed above become exclusion restrictions in system (9). As such, these can be tested using conventional F tests. We conduct the series of F tests in a sequential fashion. First, we test for stock market efficiency, that is, we test whether equation (6) is the correct specification of the last equation in system (5). This amounts to testing that the coefficients of lagged r's, i's, and q's in the q_t regression, the third equation in system (9), are all zeros. This test is denoted by T1. Given that T1 is accepted (see next section), we next test our interpretation of μ. If μ_t is the idiosyncratic to q_t, in the sense explained above, then in the regressions of r_t and i_t against lagged values of r, i, and q, the coefficients of lagged q's have to be zeros. This is so because, given lagged r's and i's, if μ_t is noise there is no information conveyed by lagged q's relevant to the determination of r_t and i_t. Denote this test by T2.

Conditional on the acceptance of T2, the system is reduced to equations (6) and (7). The autoregressive form of these equations involves only lagged values of r and i in the R&D and investment equations, and no lagged values of any variable in the q equation. This specification corresponds to the symmetry hypothesis, in which r and i move simultaneously. Taking the latter as the alternative hypothesis, we can then implement a test of the parametric restrictions implied by the technological opportunity and the inducement hypotheses, denoted by T3 and T4 respectively.

T3 tests that lagged r's do not matter in the investment equation. Under the null hypothesis, only one shock affects investment and, therefore, regressing current investment against its lagged values suffices to pick up its effects. The R&D part, however, is different: Since two shocks affect R&D, it is necessary to introduce lagged values of investment together with lagged values of R&D in the regression of current R&D expenditures. In this fashion, lagged investment will pick up the common shock, ϵ, while lagged R&D picks up the technological opportunity shock, η. Conversely, T4 tests that lagged i's do not matter in the R&D equation. The reasoning behind this test is exactly the opposite of the argument presented for T3.

2. Description of Data and Empirical Results

Our data are part of a large panel of firms in U.S. manufacturing, assembled at the NBER, from Standard and Poor's Compustat tapes. It is described in detail in Cummings, Hall, Laderman and Mundy (1984). The original universe of firms is the subset obtained by requiring that data on sales, gross capital, market value, employment, and R&D expenditures be available for all years from 1972 to 1977 with no large jumps in that period. A jump is defined as an increase in capital stock or employment greater than 100 percent or a decrease of more than 50 percent, when the change in capital is greater than two million dollars or the change in employment is greater than 500 employees, respectively. There are 1048 such firms in 1976, of which 418 belong to the scientific sector. The latter comprises firms in the chemical, drug, communication, computer, scientific instrument, and electric component industries. Table 1 shows that the scientific sector accounted for 51 percent of R&D and 27 percent of the sales generated in 1976.

Our sample consists of firms in the scientific sector for which data on R&D, investment, and the stock market rate of return was available for all nine years between 1973 and 1981. This requirement halves the number of firms to 191, basically through the elimination of relatively small firms: The 191 firms in our sample account approximately for 86 percent of R&D and sales in all the scientific sectors in 1976 (see Table 1.).

The time period in the analysis is taken to be the fiscal year of the firm. Conformably, the stock market rate of return is calculated on a fiscal year basis, from quarterly Compustat data. We use the value of q in the year before expenditures are reported. This is a result of the assumption

Table 1: 1976 Cross Section

	Universe	Scientific Sector	Sample
Number of Firms:	1048	418	191
R&D:			
Total	15549.86	7956.64	6876.00
S.D.	67.39	67.23	92.28
Average	14.84	19.03	36.00
Sales:			
Total	839776.58	225989.74	193141.75
S.D.	2906.32	1507.59	2070.77
Average	801.31	540.64	1011.21
Investment:			
Total	57149.00	17640.51	16148.47
S.D.	227.20	170.35	244.94
Average	54.53	42.20	84.55

Note: All figures are in millions of 1976 dollars.

that the decisions on R&D and investment are made at the beginning of the fiscal year. Investment and R&D expenditures are deflated to 1972 dollars.[7]

The unrestricted model given in (9) is a trivariate vector autoregression.[8] Table 2 presents the parameter estimates for this model. The sequence of hypothesis tests conducted on the unrestricted model is provided in Table 3. The first four rows provide tests of the unpredictability of q, both by separate variable and collectively. There is no evidence that q is related either to past levels of q's or to R&D (see T1(q) and T1(r)). As the third and fourth rows indicate, however, at conventional levels of significance there is evidence that q is related to past levels of investment and, as a consequence, the joint hypothesis that q is not predictable by past values of {r,i,q} is also rejected. However, none of these test statistics is even close to significance if one uses Leamer's Bayesian F, which makes an allowance for the influence of sample size on the probability of Type I error. (The critical value of the Bayesian F statistic for all the hypothesis tests reported in Table 3 is about 7.8.) Imposing the restrictions in T1 raises the residual variance in q by only 3.8 percent. In view of this fact, and the large amount of evidence in previous literature which supports weak-form efficiency of the stock market, we provisionally accept the hypothesis that q is unpredictable and turn to the remaining tests.

The underlying model is based on three unobservable factors, ϵ, η and μ. T2 tests whether the factor μ_t is idiosyncratic to q_t in the sense that it contains no information relevant to the determination of r_t and i_t. The hypothesis is not rejected. This means that there is variation in q which is unrelated to the factors moving r and i. Since the returns to R&D

Table 2. Unrestricted Parameter Estimates[a]

Variable	Equation[b]		
	r_t	i_t	q_t
r_{t-1}	1.19 (.04)	.29 (.08)	-.10 (.08)
r_{t-2}	-.31 (.06)	-.14 (.11)	-.04 (.11)
r_{t-3}	.11 (.05)	-.15 (.10)	.01 (.10)
r_{t-4}	-.00 (.03)	.11 (.07)	.10 (.07)
i_{t-1}	.05 (.02)	.70 (.04)	.06 (.04)
i_{t-2}	-.03 (.02)	.06 (.04)	-.05 (.04)
i_{t-3}	.03 (.02)	.04 (.04)	.09 (.04)
i_{t-4}	-.03 (.02)	.10 (.03)	-.11 (.04)
q_{t-1}	.01 (.02)	.08 (.04)	.01 (.04)
q_{t-2}	.03 (.02)	.07 (.04)	.01 (.04)
q_{t-3}	.01 (.02)	.07 (.04)	-.06 (.04)
q_{t-4}	.00 (.02)	-.04 (.04)	-.01 (.04)
σ^2	.042	.175	.164
d.f.	748	748	728

Notes:

[a] Estimated standard errors are in parentheses.

[b] Year dummy variables are included in the r_t and i_t equations. Industry-year interaction dummies are included in the q_t equation.

Table 3. Hypothesis Tests

		Parameter Restrictions[a]	Test Statistic	Probability Value[b]
1.	T1(r):	$B_{31}(L) = 0$	F(4,728) = 2.16	.071
2.	T1(q):	$B_{33}(L) = 0$	F(4,728) = 0.94	.442
3.	T1(i):	$B_{32}(L) = 0$	F(4,728) = 3.27	.011
4.	T1:	$B_{31}(L) = B_{32}(L) = B_{33}(L) = 0$	F(12,728) = 3.65	.001
5.	T2:[c]	$B_{13}(L) = B_{23}(L) = 0$	F(8,748) = 1.92	.053
6.	T3:[d]	$B_{12}(L) = 0$	F(4,748) = 2.58	.036
7.	T4:	$B_{21}(L) = 0$	F(4,748) = 11.04	.001

Notes:

[a] The parameter restrictions refer to the unrestricted model given in (9) in the text, which can be written fully as

$$\begin{bmatrix} r_t \\ i_t \\ q_t \end{bmatrix} = \begin{bmatrix} B_{11}(L) & B_{12}(L) & B_{13}(L) \\ B_{21}(L) & B_{22}(L) & B_{23}(L) \\ B_{31}(L) & B_{32}(L) & B_{33}(L) \end{bmatrix} \begin{bmatrix} r_{t-1} \\ i_{t-1} \\ q_{t-1} \end{bmatrix} + CV_t .$$

[b] The probability value is the marginal level of significance of the computed test statistic.

[c] T2 is conducted after imposing the restrictions in T1.

[d] T3 and T4 are conducted after imposing the restrictions in T1 and T2.

and investment are presumably major sources of income for the firm, it is of interest to assess the quantitative importance of this idiosyncratic factor for the variance in q, $\sigma_{\mu}^2/\sigma_q^2$. Estimation of the relative variances of the underlying factors is taken up later.

Given the restrictions in T2, there are at most two common factors linking r and i (and both to q), namely ϵ and η. T3 and T4 test whether a two factor representation with nonzero loadings on both factors is needed to capture the dynamic interactions between r and i, or whether a simpler version with a zero loading on one of the factors is adequate. Formally, T3 is equivalent to asking whether investment Granger-causes R&D, and T4 tests whether R&D Granger-causes investment. There is only weak evidence that investment Granger-causes R&D. The test statistic for T3 is 2.58, which is significant at the five percent but not at the one percent level, and it is far below the critical value using the Bayesian F. Imposing the restriction in T3 only raises the residual variance in r_t by a meager 1.1 percent. In sharp contrast, there is really no doubt that R&D Granger-causes investment. The test statistic for T4 is 11.04, which is both highly significant at conventional levels and well above the critical Bayesian F value.

We conclude from the tests reported in Table 3 that the dynamic movements of r, i and q can be summarized adequately in the following way: There are two factors, ϵ and η, which affect investment and both of these factors also move q. Only one of these factors, say ϵ, affects R&D. Finally, there is an additional idiosyncratic factor in q.[9] This structure implies that any movement of r is accompanied by movement in i but that there is also independent change in i, and that all changes in either r or i are also reflected in changes in q. As explained in the preceding section, this structure is not consistent with the general symmetry hypothesis which treats R&D and capital investment symmetrically in a production framework, since that hypothesis implies Granger causality running reciprocally from R&D to investment and from investment to R&D. At the same time, the structure supported by the data is also inconsistent with the stylized version of the technological opportunity hypothesis, which implies a unidirectional Granger causal ordering from investment to R&D. The empirical results are consistent with the hypothesis advanced by Lach (1986) that (at least some of) investment is induced by actual successes in the R&D process rather than just the R&D expenditure itself.[10] Whether this is the only or the most reasonable interpretation of the empirical results depends on the implications of the results for the dynamic pattern of responses of r and i to the shocks and on what we can learn about the underlying determinants of the shocks. These issues are considered in the next two sections.

3. The Restricted Model and Its Interpretation

The restricted form of the model (imposing T1-T3) can be written as

$$
\begin{aligned}
r_t &= B_{11}(L)r_{t-1} + \alpha\epsilon_t \\
i_t &= B_{21}(L)r_{t-1} + B_{22}(L)i_{t-1} + \beta\epsilon_t + \gamma\eta_t \qquad (10)\\
q_t &= \epsilon_t + \eta_t + \mu_t
\end{aligned}
$$

where α, β and γ represent the instantaneous responses to the shocks and these parameters are normalized in the q equation. The associated covariance matrix of the disturbances is

$$\Sigma = \begin{bmatrix} \alpha^2\sigma_\epsilon^2 & & \\ \alpha\beta\sigma_\epsilon^2 & \beta^2\sigma_\epsilon^2+\gamma^2\sigma_\eta^2 & \\ \alpha\sigma_\epsilon^2 & \beta\sigma_\epsilon^2+\gamma\sigma_\eta^2 & \sigma_\epsilon^2+\sigma_\eta^2+\sigma_\mu^2 \end{bmatrix}$$

It is readily verified that the model is exactly identified from the covariance matrix Σ. Table 4 present the parameter estimates for the restricted model and the residual covariance matrix. Table 5 provides estimates of the instantaneous response parameters, variances of the three shocks, and related interpretative statistics.

A number of important points about the results in Table 5 should be made. First, the factor which is common to r and i gets a much larger response parameter in the r equation than in the i equation, 2.78 versus 1.38. That is, the instantaneous response of r to ϵ is larger than for i. Second, the immediate response of i to its idiosyncratic factor η is more than eight times as large as its response to the common factor ϵ. As we noted in the introduction, for virtually all firms the variance of the rate of growth in investment is much larger than for the rate of growth in R&D. These first two points imply that the reason for this difference is <u>not</u> that investment responds more sharply to the same factor which is moving R&D, but rather that investment also responds energetically to a factor which does <u>not</u> move R&D. In order to show this result, we can use the estimates of the lag polynomials $B_{ij}(L)$ in the restricted model in (10) to retrieve the coefficients of the underlying moving average representation linking ϵ and η to r and i, denoted $A_{ij}(L)$ in (7).[11] These parameters are used to compute a decomposition of the variances of the rate of growth (and of the

Table 4. Restricted Parameter Estimates[a]

Variable	Equation[b]		
	r_t	i_t	q_t
r_{t-1}	1.23 (.04)	.35 (.08)	
r_{t-2}	-.32 (.05)	-.16 (.11)	N/A
r_{t-3}	.11 (.05)	-.14 (.10)	
r_{t-4}	-.03 (.03)	.07 (.07)	
i_{t-1}		.69 (.04)	
i_{t-2}	N/A	.09 (.04)	
i_{t-3}		.01 (.04)	
i_{t-4}		.11 (.03)	
σ^2	.043	.178	.173
d.f.	756	752	740

$$\hat{\Sigma}^c = \begin{bmatrix} .0432 & & \\ .0213 & .1777 & \\ .0155 & .0219 & .1732 \end{bmatrix}$$

Notes:

[a] Estimated standar errors are in parentheses.

[b] Year dummies are included in the r_t and i_t equations, and industry-year interaction dummies in the q_t equation.

[c] $\hat{\Sigma}$ is the estimated covariance matrix of the residuals from the restricted model for the vector (r_t, i_t, q_t).

Table 5. Interpretative Statistics from Restricted Model

	Parameters[a]	Estimate
1.	α	2.78
2.	β	1.38
3.	γ	11.70
4.	σ_ϵ^2	.00557
5.	σ_η^2	.00123
6.	σ_μ^2	.1664
7.	$\beta^2\sigma_\epsilon^2/\sigma_I^2$	.059
8.	σ_μ^2/σ_q^2	.961
9.	$V(\epsilon)$	1.18
10.	$V(\eta)$	1.22

Notes:

[a] The parameters α, β, γ, σ_ϵ^2, σ_η^2, and σ_μ^2 are estimated from the estimated residual covariance matrix $\hat{\Sigma}$ given in Table 4.

levels) of r and i into a part accounted for by each of the shocks, ϵ and η.[12] This decomposition indicates that 93 percent of the variance in the growth rate of investment is due to the variance in the idiosyncratic factor η. However, it is the variance in the common factor ϵ which accounts for 91 percent of the variance in the (log) level of investment. Thirdly, the bulk of the variance in the unpredictable part of i is due to the idiosyncratic factor. As row 7 in Table 5 shows, only about six percent of the variance in i is due to the common factor. Fourth, although the instantaneous responses of r and i to ϵ differ, the moving average coefficients imply that the long run responses of r and i to ϵ are essentially equal in magnitude. The fifth point is that about 96 percent of the variation in q is idiosyncratic in the sense that it is unrelated both to r and i.[13] Since R&D and physical capital surely constitute the most important income-generating assets for a firm, the fact that only four percent of variations in q are related to movements in investment in these assets is very striking.[14]

The coefficients of the moving average representation of the model describe the pattern of responses over time of r and i to the underlying shocks ϵ and η. Figure 1 presents the dynamic responses of r to ϵ ($A_{11}(L)$) and of i to ϵ ($A_{21}(L)$). Several prominent features of these patterns should be noted. Turning first to $A_{11}(L)$, we observe that the response of R&D to ϵ is rapid and sharp, and then very persistent. The peak effect occurs during the first year or two, after which there is a very slow decay. The overall impression is that the effect of ϵ on R&D is almost immediate and essentially permanent. This implies that variations in R&D, after removing deterministic components, are caused by very recent events since the impact of ϵ on future r's is nearly constant after the first few periods and hence cannot be responsible for changes in r.[15] The response of investment to ϵ is considerably slower than for R&D. The moving average coefficients rise sharply for a long period of time and then begin a slow descent. The clear impression is again one of a very persistent effect on investment, but one which takes a longer time to be felt. This implies that variations in investment (insofar as they are induced by ϵ), after removing deterministic components, are generated not only by recent events but also by those which occurred some time in the past. Figure 2 presents the moving average coefficients for the response of investment to the idiosyncratic factor η, denoted $A_{22}(L)$. Here the pattern is entirely different. The peak impact occurs immediately and is followed by a rapid geometric decay at the rate of about 25 percent per year for the first four years and about seven percent thereafter. In short, the variations in investment which are not correlated with variations in R&D are due to events which have a large initial but highly transitory impact on investment. It is also clear that since ϵ has a permanent effect it is primarily responsible for the determination of the level of investment, while η is primarily responsible for determining its rate of growth.

The parameter estimates can also be used to construct what may be viewed as "benefit-cost" ratios of unanticipated changes in R&D and investment, based on their stock market valuations. A unit increase in ϵ induces, as an optimal response by the firm, an adjustment in the entire stream of future r and i. At the same time, this increase is ϵ is associated with an increase in the discounted value of the stream of net benefits (above and beyond the costs of the additional r and i), as

FIGURE 1

MOVING AVERAGE COEFFICIENTS A(L)

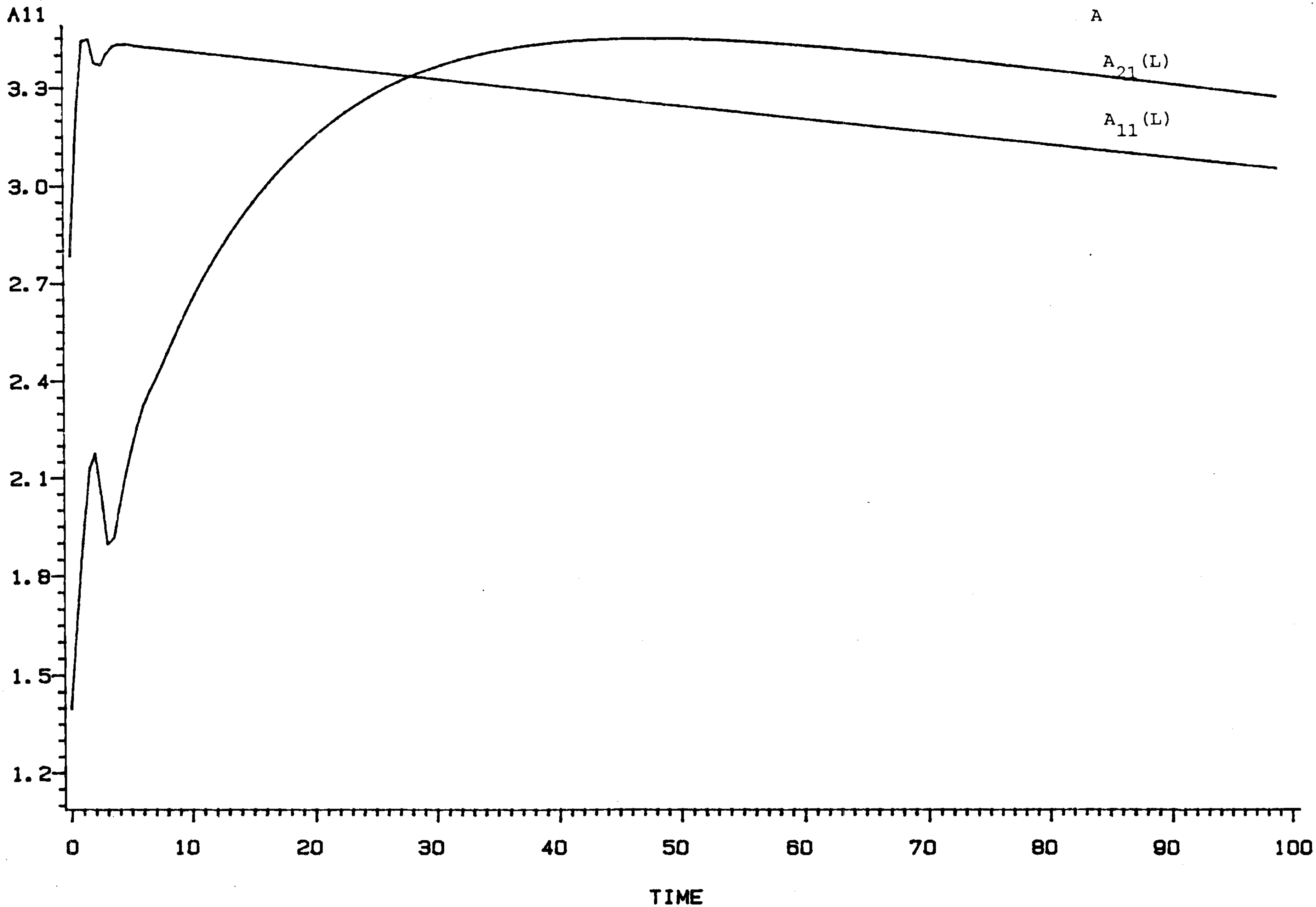
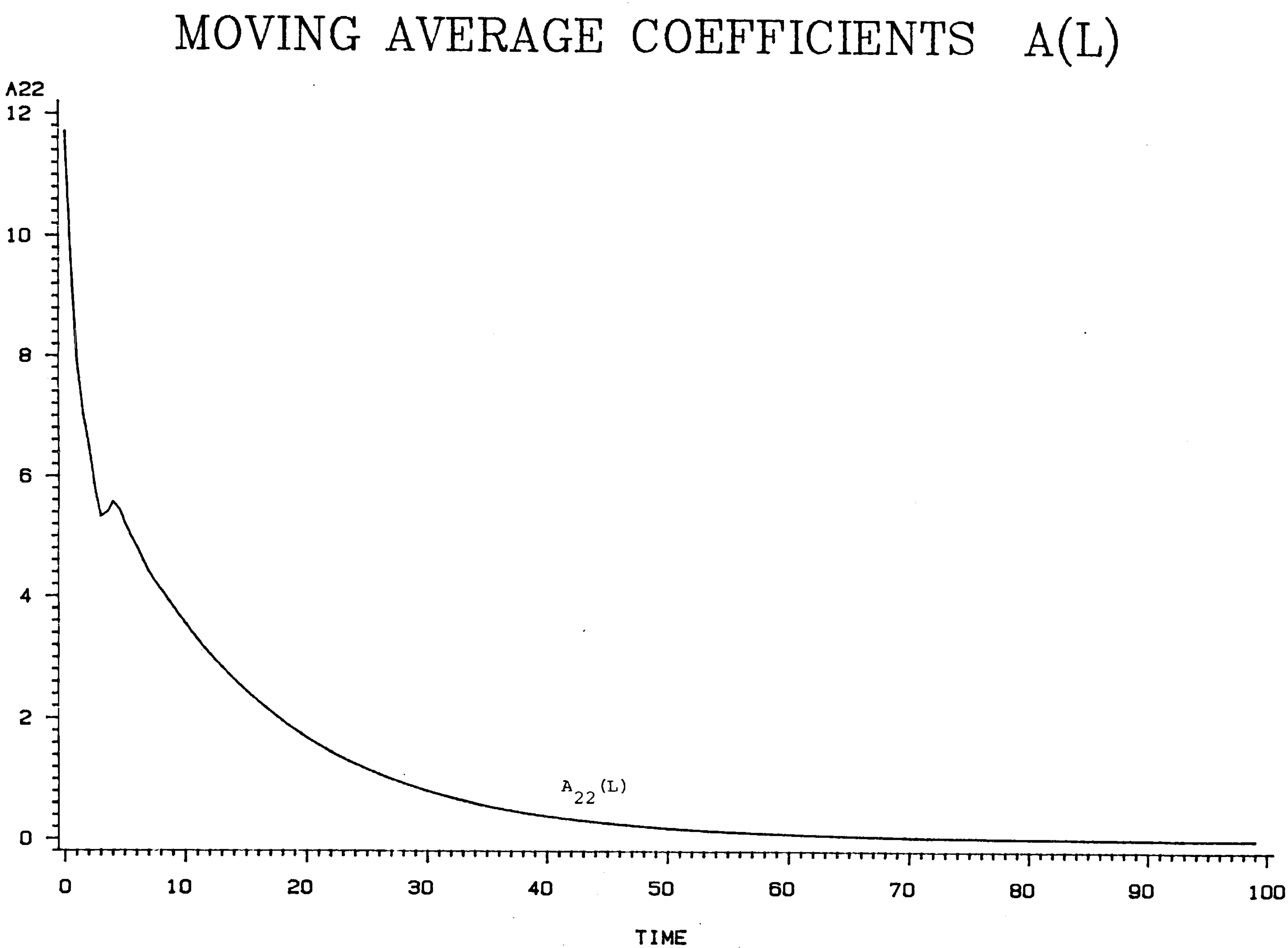


FIGURE 2


MOVING AVERAGE COEFFICIENTS A(L)
A22
12
10
8
6
4
2
0
A22(L)
0
10
20
30
40
50
60
70
80
90
100
TIME

reflected by the instantaneous one percent increase in q. This allows us to compute a benefit-cost ratio for the changes in R&D and investment which are induced by ϵ. Exactly the same procedure is followed to analyze the value of the changes in investment (alone) which are induced by η.[16]

The results (rows 9 and 10 of Table 5) indicate that the benefit-cost ratios for the changes induced by ϵ and η are 1.18 and 1.22, respectively (using a discount factor of 0.05). This means that events (represented by ϵ) that cause a combined increase in the stream of both R&D and investment of $100 are also associated with an increase in the market value of the firm (net of these costs) of $18. Events (represented by η) which cause only an increase in the stream of investment of $100 are associated with a rise in the market value of $22.

4. An Alternative Interpretation

The parameter restrictions supported by the data imply a particular Granger causal ordering between R&D and investment. Among the hypotheses discussed, only the inducement hypothesis motivates this ordering. This hypothesis requires that η be interpreted as an R&D success shock, but we do not have any direct evidence to support this interpretation. To obtain such evidence, one would need direct and serviceable measures of R&D success at the firm level which are not available in the data set.

There is a more traditional interpretation of the shocks which identifies ϵ and η as demand and supply (factor prices) effects, and which is also consistent with the observed Granger ordering. Under this interpretation, the hypothesis tests in Section 2 check for the presence or absence of demand and supply factors in the determination of R&D and investment. The first interpretation treats η as a demand shock and ϵ as the supply shock. This interpretation is not supported by the data. The immediate and highly transitory response of investment to η does not suggest a demand shock and it is completely implausible to believe that demand shocks have no impact on R&D, as required by the model under this interpretation (see, e.g., Schmookler (1966)). The alternative, interpreting ϵ as a demand shock and η as a supply shock, is more plausible both in terms of the response patterns and the assumption that factor prices affect investment but not the level of R&D (as opposed to the "factor bias" of R&D effort). To examine this alternative, we now investigate the determinants of the shocks.

The unobservable factors in the model (ϵ,η,μ) represent the contemporaneous shocks in the underlying variables which are driving the observable variables in the model (r,i,q). We examine whether movements in these factors can be explained by contemporaneous "news" in measurable economic variables. Of course, neither these factors nor the news in underlying variables can be directly observed, but both can be estimated. Estimates of the sequence of unobserved shocks $\{\hat{\epsilon},\hat{\eta},\hat{\mu}\}$ are obtained using the residuals from the restricted model (10) and the parameter estimates of α, β and γ. Given a set of explanatory variables, we estimate a second-order vector autoregression and use the residuals from these regressions as estimates of the news in these variables. The procedure then is simply to regress the sequence of unobserved shocks $\{\hat{\epsilon},\hat{\eta},\hat{\mu}\}$ against the news in the explanatory variables of interest, separately for each shock. These regressions have no structural interpretation and should be thought of as reduced form associations.

We are limited in the choice of explanatory variables by the need to have a continuous time series for all firms (balanced data) for the entire sample period. We use two variables to capture demand and factor prices, namely undeflated sales denoted by s and a measure of average variable costs, denoted by c. In addition, we include a rough measure of cash-flow or liquidity of the firm, namely net operating income before depreciation, denoted by ℓ. All three variables are firm-specific. Since the restricted model from which ϵ, η and μ are estimated includes year and/or industry-year effects, there is no scope for using macro or industry-level variables to capture factors which are common to all firms.

The empirical results are presented in Table 6 and can be summarized succinctly. The news in factor prices (as measured by average variable cost) has a negative impact both on ϵ and μ, but it has no measurable effect on η. The news in the firm's own sales has a strong positive effect on all three factors, ϵ, η and μ. The news in our measure of liquidity has no effect on either ϵ or η, which also implies no effect on either R&D or capital investment. This result may reflect the crudeness of the measure of liquidity, or the fact the firms in our sample are large and are less likely to be liquidity constrained (see Table 1). There is also a positive and marginally significant effect of the news in cash-flow on μ. However, this is probably just a consequence of the fact that the stock market is valuing the expected stream of cash-flows and hence should react positively to any news in current cash-flow.[17,18]

These results are inconsistent with the interpretation of ϵ as the demand shock and η as the supply shock. If this interpretation were correct, one would expect factor prices to affect η but not ϵ and for

Table 6. Explanatory Regressions for Unobserved Factors[a]

Variable[b] ("news")	Unobserved Factor[c]		
	ϵ	η	μ
1. c	-.13* (.05)	.00 (.02)	-1.28* (.25)
2. s	.21* (.02)	.08* (.01)	.75* (.13)
3. ℓ	.01 (.01)	-.00 (.00)	.04 (.02)
R^2	.10	.08	.10
d.f.	761	761	761

Notes:

[a] Estimated standard errors are in parentheses. An asterisk denotes statistical significance at the five percent level.

[b] The variable represents the residuals for that equation from a (second-order) vector autoregresson for all variables, including year dummies. All variables are in logarithms.

[c] The unobserved factors are estimated from the residuals in (10), as described in the text.

sales not to affect η. The empirical results tell exactly the opposite story. We conclude that the data do not support any interpretation of the unobservables ϵ and η which is based on the distinction between demand and factor price shocks.

Concluding Remarks

This paper analyzes empirically the interaction among R&D, capital investment, and the stock market rate of return of 191 firms in science-based industries for the period 1973-1981. The basic model has the form of a dynamic factor analysis in which these three endogenous variables are determined by the evolution of three unobservable stochastic factors. The main empirical findings can be summarized succinctly. The data indicate that the interaction between R&D and investment is unidirectional. R&D Granger-causes investment but investment does not Granger-cause R&D, and the stock market rate of return is (with some qualifications) white noise. The model that generates this causal ordering is one in which R&D and investment respond to a single common factor, while investment also responds to an idiosyncratic factor which does not affect R&D, and the stock market rate of return is used as an indicator of all three stochastic factors. The factor which is common to R&D and investment accounts for 91 percent of the variance in the (log) level of investment and its impact on investment is very persistent over time. The idiosyncratic factor in investment accounts for 93 percent of the variance in the rate of growth of investment. The response pattern of investment to this idiosyncratic factor is sharply different, exhibiting a large initial reaction which dissipates rapidly over time. The response of R&D to the common factor is also very persistent of time, but it is distinctly faster than for investment. An increase in the common factor induces increases in the streams of both R&D and investment. A combined increase of $100 in both R&D and investment is accompanied by a rise in the market value of the firm (net of these costs) of $18. Similarly, a $100 increase in investment induced by the idiosyncratic factor is associated with an increase in the market value of $22. Finally, 96 percent of the variance in the stock market rate of return is accounted for by factors other than those associated with movements in R&D and investment. Additional empirical results indicate that the data do not support any distinction between the common and idiosyncratic factors which is based on demand and supply considerations.

The causal ordering between R&D and investment is consistent with the inducement hypothesis. It is not compatible either with neoclassical investment theory which treats capital and R&D investments symmetrically, or with the strict version of the technological opportunity hypothesis. However, these empirical findings are based on a relatively short time series. While we do not consider this to be a serious limitation for the symmetry hypothesis, it may well be that the lag structures and feedback effects linking R&D and investment are both longer and more subtle than can be detected with our data. A more complete investigation of the technological opportunity and inducement hypotheses requires both a longer time series on R&D and investment, and informative measures of technological opportunities and R&D successes at the firm level.

FOOTNOTES

* The authors are from Columbia University, and the London School of Economics and the National Bureau of Economic Research, respectively. We would like to thank Zvi Griliches and the participants of the NBER Summer Institute on Productivity and Technical Change for useful suggestions on an earlier draft of this paper. The second author gratefully acknowledges financial and technical support from the C.V. Starr Center for Applied Economics at New York University.

[1] This arbitrary decomposition of the information set is forced upon us by the data. Having only three observables allows us to identify, at most, up to three sources of movements in $\bar{\Omega}_t$. Even this is not true in general: It depends on the particular way in which the different components of $\bar{\Omega}_t$ affect our three observed variables. A decomposition of the information set into fewer than three components is testable.

[2] Deterministic components in $\{x_{1t}, x_{2t}, x_{3t}\}$ are ignored in (5). In the empirical work, time dummy variables are added to all the equations and these should pick up any deterministic component that may exist. See also fn. 8.

[3] Note that the q equation in (5) is not the correct representation of equation (4) because the latter implicitly assumes that the stock market is efficient. Since this proposition is going to be tested, the specification in (5) makes it easier to understand the nature of the test.

[4] Except for the special case of strong separability between capital and R&D in the production function (and in the costs of adjustment, if they are present).

[5] It is assumed that the roots of the polynomial equations associated with $A_{ij}(L)$ all lie outside the unit circle (This condition will be checked empirically later). Equation (9) is obtained as follows: pre-multiply both sides of (8) by the inverse of $A(L)$ and rearrange the system in such a way that r_t, i_t and q_t are on the LHS. Divide each equation by the coefficient of its LHS variable. Finally, substitute for the current values of Z_t in the RHS of each equation from the remaining equations.

[6] The year dummies added to each equation ought to pick up any common factors across firms (such as business cycle effects), and ensure that the errors are uncorrelated across them.

[7] See Cummings, Hall, Laderman, and Mundy (1984). A fixed investment and an R&D "deflator" were used (Tables 3 and 5). The latter is a weighted average of the hourly compensation index (.49) and of the implicit deflator in the nonfinancial corporations sector (.51).

[8] In order to capture deterministic components, we include year dummies in the equations for investment and R&D, and industry/year interaction

dummies in the q equation. We actually tested the interactive dummy specification against the inclusion of only year effects, and followed the results of those tests for each equation.

[9] We also conducted the preceding sequence of hypothesis tests in a more general specification of the model which allows both for fixed firm effects and nonstationary coefficients. This model was estimated using a GLS procedure with instrumental variables, as described by Holtz-Eakin, Newey and Rosen (1985). The conclusions reported in the text remain unchanged.

[10] Two remarks are in order. First, one can easily show that the extended version of the technological opportunity hypothesis allows for reciprocal Granger causality between r and i, but it requires that investment not be affected by the most recent r's. The parameter estimates for the investment equation in Table 2 do not meet this requirement. Second, one can show that when learning from R&D successes is incorporated into the inducement hypothesis, it implies the additional requirement that R&D be affected by lagged investment, but not necessarily by the most recent lags. The estimates in Table 2 do not support this requirement either. Some qualifications to these findings are presented in the concluding remarks.

[11] Let $A_{11}(L)$, $A_{21}(L)$ and $A_{22}(L)$ be the moving average polynomials for the effects of ϵ on r, ϵ on i, and η on i, respectively. Also let $B_{11}(L)$, $B_{21}(L)$ and $B_{22}(L)$ be the autoregressive polynomials of lagged r's in the r equation, lagged r's in the i equation, and lagged i's in the i equation, respectively. Then it can be shown that the moving average coefficients are obtained from the following recursion formulas:

$$A_{11,t} = \sum_{j=1}^{4} B_{11,t} A_{11,t-j} \qquad A_{11,0} = 1$$

$$A_{22,t} = \sum_{j=1}^{4} B_{22,t} A_{22,t-j} \qquad A_{22,0} = 1$$

$$A_{21,t} = \sum_{j=1}^{4} B_{22,t} A_{21,t-j} + (\alpha/\beta) \sum_{j=1}^{4} B_{21,t} A_{11,t-j} \qquad A_{21,0} = 1$$

We also note that the estimates of the autoregressive coefficients in Table 4 satisfy the condition that all the roots of each polynomial lie outside the unit circle.

[12] The variance of the rate of growth of investment $\mathrm{Var}(\Delta i)$ is

$$\mathrm{Var}(\Delta i) = \left[A_{21,0}^2 + \sum_{j=1}^{\infty} (A_{21,j} - A_{21,j-1})^2\right]\sigma_\epsilon^2 + \left[A_{22,0}^2 + \sum_{j=1}^{\infty} (A_{22,j} - A_{22,j-1})^2\right]\sigma_\eta^2.$$

The variance of the log level of investment $\mathrm{Var}(i)$ is

$$\mathrm{Var}(i) = \sigma_\epsilon^2 \sum_{j=0}^{\infty} A_{21,j}^2 + \sigma_\eta^2 \sum_{j=0}^{\infty} A_{22,j}^2 .$$

[13] In a study of R&D, patents and q based on firm data, Pakes (1985) found that about 95 percent of the variance in q was unrelated to variation in R&D. We originally thought that this result was simply a

reflection of the fact that R&D is only a small part of the overall investment budget of the firm, the bulk being capital investment. Our current results dispel this interpretation.

[14] It may appear that this finding provides indirect support for the "excess volatility" hypothesis, though the latter actually concerns a comparison of the variance in stock prices and the variance in the discounted value of expected earnings (or dividends in some versions). Our result, however, simply shows that most of the variation in q is unrelated to variations in new R&D and capital investment. One important reason for caution in interpreting this finding as support for that hypothesis is that variations in q also reflect revaluations of the existing stocks of R&D and capital, which by themselves imply changes in the expected stream of earnings of the firm.

[15] In a study of R&D, patents and q, Pakes (1985) obtained a similar characterization of the time path of the response of R&D to the (single) common shock in his model.

[16] In the case of ϵ, the moving average coefficients provide the changes in the log level of R&D and investment. These imply the sequence of increases in R and I, $\{A_{11,\tau}R_{t+\tau}, A_{21,\tau}I_{t+\tau}\}$. Evaluating the sequence $\{R_{t+\tau}, I_{t+\tau}\}$ at the overall mean (over N and T) of R&D and investment, the discounted value of the costs associated with a unit increase in ϵ is

$$C(\epsilon) = \bar{R}\sum_{\tau=0}^{\infty} A_{11,\tau}d^{\tau} + \bar{I}\sum_{\tau=0}^{\infty} A_{21,\tau}d^{\tau} \quad (\sim\$20.3 + \$42.1)$$

where d is the discount factor and the first term in the RHS represents the costs associated with R&D. A one percent increase in the stock market value, evaluated at the overall mean, implies an absolute increase of $11.2. By similar calculations,

$$C(\eta) = \bar{I}\sum_{\tau=0}^{\infty} A_{22,\tau}d^{\tau} \quad (\sim \$50.7).$$

[17] Two points should be noted. First, since all variables used in this paper (including q) are constructed on the basis of the firm's fiscal year, from a strict point of view only the contemporaneous "news" in the explanatory variables should affect the factors ϵ, η and μ. To test this implication, we re-estimated the regressions in Table 6, including not only the contemporaneous but also three lagged values of the "news" in each explanatory variable. The null hypothesis that lagged values are jointly zero is easily accepted in the equations for η and μ. The test statistic $F(9,752)$ is .097 and 1.55 respectively. For the ϵ equation, the test statistic is 4.92 and the hypothesis is formally rejected. A closer examination reveals that the rejection is due exclusively to nonzero coefficients on first lagged values. The pattern of results is nonetheless similar to those reported in Table 6. Second, we also included as an explanatory variable the number of patents applied for (and granted) by the firm. (This required some reduction in sample size because of missing observations.) There is no evidence of any effect of the news in patents on ϵ, η or μ. This is not surprising, considering

previous research which indicates large measurement error in patent counts. See Pakes and Griliches (1984).

[18] The estimates in Table 6 give the effects of "news" in the explanatory variables on the shocks ϵ, η and μ. Together with the parameters α, β and γ from Table 5, we can derive the effects of the "news" on the endogenous variables r, i and q. For example, the elasticities of r, i and q with respect to the "news" in factor prices and sales are: $\partial r/\partial c = -.36$, $\partial r/\partial s = .58$, $\partial i/\partial c = -.18$, $\partial i/\partial s = 1.23$, $\partial q/\partial c = -1.41$, and $\partial q/\partial s = 1.04$. These estimates of the elasticities seem rather reasonable, both in terms of their signs and magnitudes.

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