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The Dynamics of Resource Allocation in Research Organizations

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Abstract

As a first step towards understanding the evolution of small groups in firms, this paper develops and tests a simple decision-theoretic model of research-unit evolution in which, as managers resolve their uncertainty over time, they shut down under-performing units and remove under-performing unit heads. The selection process generates several testable hypotheses about how unit and head characteristics affect the assignment of heads to units and resource allocation within the firm. Data on research units in firms is used to test the model and estimate the relative importance of the different effects on resource allocation.

JEL Codes: **O32**: Management of Technological Innovation and R&D, **M12**: Personnel Management, **J32**: Non-wage Labor Costs and Benefits.

Keywords: span of control, management, innovation, small group

1. Introduction

Managers in firms often have to allocate resources to small groups without having a complete understanding of the projects being pursued or the abilities of the group members. This

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is particularly problematic when group members have specialized skills, as is the case in research organizations. In firms that have research units, two interesting problems arise. First, managers that allocate resources within the firm, lacking technical expertise, are often unsure about the quality of the projects pursued by the research-unit heads. Second, they are often unsure about the quality of the heads themselves. Complicating the problem further, research units sometimes produce no output for long periods of time, in contrast to manufacturing or marketing units. In this case, managers have to base their decision of whether to continue a project solely on their beliefs. Further, a research-unit head that is poorly suited for the unit's project can lower the expected output dramatically (see Gilman (1992) and Thorne (1992) for a discussion of these issues). Therefore, it is often difficult to determine whether the head of a unit should be replaced or the project should simply be abandoned.

In the next section, a simple decision-theoretic model of research-unit evolution with the above features is developed. A production function with uncertainty is used, in which both the head and the project must be high quality in order for the unit to have a higher-than-average chance of success. As managers resolve their uncertainty over time, they shut down under-performing projects and remove heads believed to be of low quality. In contrast to previous worker selection models that focus on wage changes (Harris and Holmstrom (1982) and Macleod and Malcolmson (1988)), the focus here is on how selection (shutting down projects and removing heads) causes research-unit size and the head's control over resources to change over time.

This paper adds to the literature on decentralization and influence over resource allocation by emphasizing dynamics. Decentralization is typically discussed in a static context, with a focus on how exogenous changes in the environment affect the organization (Milgrom and Roberts (1992), Aghion and Tirole (1995)). Previous empirical work on the control of research-unit heads over resources (Katz and Allen (1997)) also has this feature - the analysis is essentially static.

This paper also addresses an issue that is underemphasized in the principal agent literature: Often mid-level managers have to make resource allocation decisions in a setting in which they do not control the compensation of their workers. In this case, managers

may be unable to get their project heads to credibly reveal private information. In such an environment, managers must base decisions on their beliefs alone. Leaving aside the issue of the optimality of such an organizational structure, this paper focuses on the effects of such a decision-making environment on resource allocation in a dynamic setting.

The selection process generates several falsifiable predictions, which are described in the next section: 1) Factors that affect the managers' prior beliefs have lasting effects. Holding the stream of output realizations constant, if the initial beliefs about either the project or the head are more favorable, the amount of resources allocated to the unit is higher in every future period. This suggests that indicators of quality that can be observed at the time the head is assigned to the project are important determinants of control over resources, and offers one reason why "heavyweight" project heads have more influence over resource allocation - heavyweights are initially believed to be high-quality types.¹ 2) Heads who obtain R&D experience before joining their current unit receive more resources than heads who lack previous experience. 3) Incumbent heads receive more resources than new heads. 4) Older units receive more resources than new units. 5) Unassigned heads who are believed to be better are assigned to projects that are believed to be better. 6) If a new head is assigned to a pre-existing project and at some point thereafter the unit's performance declines, the head is always replaced before the project is abandoned. Similarly, if an experienced head is assigned to a new project and at some point thereafter the unit's performance declines, he will always be assigned a new project if the current one is abandoned. 7) Conditional on survival, older units tend to have more resources (as measured, for example, by the number of workers under the head's supervision), and have more variation in size.

In Section 3, survey data on research units in firms is used to test the predictions of the model and to estimate the relative importance of the different effects on the head's span of control. Unit size, as measured by the number of scientists in the unit, is found to be positively related to the head's years of education and years of R&D experience before becoming unit head, two indicators of head quality that can be observed at the time of hire. Unit size is also increasing in the tenure of the head and in the age of the unit. Following the empirical results, Section 4 concludes.

¹Heavyweight project heads (Wheelwright and Clark (1992)) come from the ranks of senior management.

2. The Model

Consider a manager in a firm who is able to select projects and project heads from a pool and match them up. Projects are either good or bad, and heads are also either good or bad. Assume that the manager is unable to directly observe project and head types. Assume that heads are either incapable of observing their own type and the project types, or that they cannot credibly reveal this information to the manager. Heads of units simply obtain resources and work on the projects they are assigned to.² Projects exist until they are shut down, and heads remain heads until they are removed.

Most of the analysis below focuses on the relationship between the manager and a single representative research unit.³ This focus is enough to describe the main forces affecting managerial decision-making in this setting. The types of managerial decisions considered below are: starting and shutting down projects, assigning either experienced or inexperienced heads to new projects, removing incumbent heads, and assigning either experienced or inexperienced heads to ongoing projects that require new leadership.

Each time period, a unit produces an output with probability a and produces nothing with probability $1 - a$. The probability a depends on the project type *and* the head type: If the project is a good project *with a good head*, then $a = a_h$. If the project is a bad project, *or if the project has a bad head*, then $a = a_l$, where $a_h > a_l$. Therefore, only units with *good projects and good heads* can potentially perform better than other units. This reflects the nature of the environment described in the introduction; firms need both good projects and good researchers in order to succeed. These assumptions determine a time series of independent Bernoulli draws - each draw either a success or failure - where the probability of success is either a_h or a_l . The manager's problem is to try to figure out whether $a = a_h$,

²The model departs from the recent game-theoretic literature on the management of innovation (Aghion and Tirole 1994a, 1994b) by focusing entirely on the resource allocators' decision process. The gain from this simplification is that several clear results on the effects of selection are obtained. Aghion and Tirole (1994a, 1994b) allow for researcher effort choices, but implicitly assume that there is no uncertainty about head and project quality, so selection and the evolution of beliefs play no role in their analysis.

³In the discussion below, a *unit* is a small group working on a single project. A unit is said to be shut down when its project is shut down (so units can outlive heads but not projects), and for much of the discussion the terms project and unit can be used interchangeably.

and if it does not, then take the appropriate corrective action.

Suppose that the manager has a pool of new heads and a pool of new projects. Suppose that all new heads are identical from the manager's point of view and are believed to be good with probability p_0 , and that all new projects are also identical ex ante and are believed to be good with probability q_0 . If a new head is assigned to a new project, the initial belief that both are good is λ_{00} , where $\lambda_{00} = p_0 q_0$. Now suppose the head and the research project stay together for $s + t$ periods, where s represents the number of periods that output occurs, and t represents the number of periods that output does not occur. Denote the resulting joint probability that both the head and the project are good by λ_{st} , where by Baye's Rule,

$$\lambda_{st} = \frac{a_h^s (1 - a_h)^t \lambda_{00}}{a_h^s (1 - a_h)^t \lambda_{00} + a_l^s (1 - a_l)^t (1 - \lambda_{00})}. \quad (2.1)$$

Denote the unconditional probability that the head is good by p_{st} , where

$$p_{st} = \frac{a_h^s (1 - a_h)^t p_0 q_0 + a_l^s (1 - a_l)^t p_0 (1 - q_0)}{a_h^s (1 - a_h)^t p_0 q_0 + a_l^s (1 - a_l)^t (1 - p_0 q_0)}. \quad (2.2)$$

Denote the unconditional probability that the project is good by q_{st} , where

$$q_{st} = \frac{a_h^s (1 - a_h)^t p_0 q_0 + a_l^s (1 - a_l)^t (1 - p_0) q_0}{a_h^s (1 - a_h)^t p_0 q_0 + a_l^s (1 - a_l)^t (1 - p_0 q_0)}. \quad (2.3)$$

Equations (2.1)-(2.3) completely describe the manager's beliefs about the head and the project after s periods of output and t periods of no output. The Bayesian updating process implies that as the number of periods $s + t$ gets large, the manager eventually learns the truth about a , because eventually the proportion of periods in which output has occurred is either a_h or a_l , whichever is the true underlying parameter. If the manager observes poor performance (if a_l is the most likely value of a), then the manager relies on his beliefs to determine the likely cause - is it a bad head, a bad project, or both? The results presented below describe how the manager makes optimal decisions in this setting.

Each period, the manager believes that an output will be produced with a probability given by the following expression:

$$\Pr\{\text{output occurs in period } s + t\} = a_l + \lambda_{st}(a_h - a_l). \quad (2.4)$$

In order to connect the implications of expressions (2.1)-(2.4) to testable predictions about resource allocation, the following assumption is made below:

The Resources Assumption: Assume that the amount of resources that the manager allocates to the unit is increasing in his belief about the likelihood that output occurs.

Note that, given the assumptions made above on a , the manager's beliefs do not depend on the amount of resources allocated to the unit. Thus, the assumptions rule out an environment in which the manager is able to adjust the resource allocation in order to improve his learning about the project and the head. This simplifies the analysis.

Result 1: λ_{st} is increasing in λ_{00} . Therefore, any factors that increase the manager's priors about head or project quality lead to more resources being allocated in every period as long as the head and the project are kept together.

Proof: The derivative of λ_{st} with respect to λ_{00} is

$$\frac{\partial \lambda_{st}}{\partial \lambda_{00}} = \frac{a_h^s(1 - a_h)^t a_l^s(1 - a_l)^t}{[a_h^s(1 - a_h)^t \lambda_{00} + a_l^s(1 - a_l)^t(1 - \lambda_{00})]^2},$$

which is positive. ■

Result 1 clearly also holds for cases in which either the head or the project is not new: for any initial p , q , and $\lambda = pq$, future values of λ are increasing in the initial value. In the empirical section, the head's years of education is used as a proxy for the manager's prior belief about his quality.

Since the firm only obtains a_h if both its project and head are good, and since *Result 1* shows that higher values of λ today are associated with higher future values of λ , the manager optimally bases his decisions entirely on whether it is possible to increase the joint probability that the head and the project are good. In what follows, it is assumed that every period the manager can replace either the head or the project or both, and that the transactions costs associated with these actions are negligible.

Lemma 1: If replacements must come from the pool of new heads and projects, then the manager keeps an incumbent head with his project as long as $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$.

That is, as long as the past observations of output and non-output are more likely to come from a good project with a good head than from either a bad project or a good one run by a bad head, then the head and the project will be kept together.

Proof: If a new head is assigned to an existing project, the probability that they are both good is given by $p_0 q_{st}$. If an existing head is assigned to a new project, the probability that both are good is given by $p_{st} q_0$. If the transactions costs of replacing the head or the project are negligible, then the manager keeps an incumbent head with his project as long as $\lambda_{st} \geq p_0 q_{st}$, $\lambda_{st} \geq p_{st} q_0$, and $\lambda_{st} \geq p_0 q_0$. First consider the first inequality. Using standard results from probability theory,

$$\begin{aligned} \lambda_{st} &= \Pr\{\text{the head is good given that the project is good}\} q_{st} \\ &= \frac{a_h^s (1 - a_h)^t p_0}{a_h^s (1 - a_h)^t p_0 + a_l^s (1 - a_l)^t (1 - p_0)} q_{st}, \end{aligned} \tag{2.5}$$

Subbing in for λ_{st} and canceling the q_{st} terms, $\lambda_{st} \geq p_0 q_{st}$ if and only if

$$\frac{a_h^s (1 - a_h)^t p_0}{a_h^s (1 - a_h)^t p_0 + a_l^s (1 - a_l)^t (1 - p_0)} \geq p_0.$$

Simple algebra shows that this inequality holds as long as $a_h^s (1 - a_h)^t \geq a_l^s (1 - a_l)^t$. A similar argument establishes that $\lambda_{st} \geq p_{st} q_0$ as long as $a_h^s (1 - a_h)^t \geq a_l^s (1 - a_l)^t$. Finally, using the expression for λ_{st} in equation (2.1), simple algebra shows that $\lambda_{st} \geq p_0 q_0$ as long as $a_h^s (1 - a_h)^t \geq a_l^s (1 - a_l)^t$. ■

Of course, in some cases for reasons outside the scope of the formal model presented here, the manager may wish to transfer a head even though the head has not been underperforming. The model can be used to consider the effects of such a transfer on resource allocation. Similarly, new heads may be assigned to existing projects rather than just new ones. The following result examines these possibilities and determines the effects of a researcher's previous experience on resource allocation.

Result 2: Heads who obtain R&D experience before joining their current unit receive more resources than heads who lack previous experience, holding project characteristics constant.

Proof: Suppose that project A , of arbitrary quality q , requires a head. There are two candidates for the position. One is a researcher who has previous experience as head of project B for $s + t$ periods and was not removed, but is now available for reassignment. The other is a new researcher. In this case, the expected output is higher with the experienced head as long as $p_{st}q \geq p_0q$. Using the expression for p_{st} in equation (2.2), simple algebra shows that $p_{st} \geq p_0$ as long as $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$. By Lemma 1, the condition $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$ is the same one that ensures that the head is not removed and that the project is not shut down. Therefore, since the experienced researcher was not removed, he is believed to be better than the new researcher, and as a result receives more resources. ■

The next result shows that incumbent heads receive more resources than new heads. It is worth clarifying the distinction between Results 2 and 3. Result 2 refers to R&D experience obtained on projects other than the current one, and Result 3 refers to experience obtained as head of the current project.

Result 3: Incumbent heads receive more resources than new heads, holding other things constant.

Proof: Suppose that the manager has the same unconditional beliefs p_{st} about two researchers and that there is a single project that the manager believes is good with probability q_{st} . Assume that one of the researchers has been head of the project for $s + t$ periods while the other has not. In this case, because the manager has the same unconditional beliefs about the two researchers, the *only difference* between the two researchers is that one has been with the unit and the other has not. For the incumbent head a stream of observations on the output of the head *with the project* is available. In this case, the manager allocates more resources to the project if the incumbent head is in charge as long as $\lambda_{st} \geq p_{st}q_{st}$. The following argument establishes that $\lambda_{st} \geq p_{st}q_{st}$ as long as $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$. When combined with Lemma 1, this establishes that as long as an incumbent head has not been removed, he receives more resources than a new head would, holding other things constant.

Sub in for λ_{st} using expression (2.5) and sub in for p_{st} using expression (2.2) to see that $\lambda_{st} \geq p_{st}q_{st}$ if and only if

$$\frac{a_h^s(1 - a_h)^t p_0}{a_h^s(1 - a_h)^t p_0 + a_l^s(1 - a_l)^t(1 - p_0)} \geq \frac{a_h^s(1 - a_h)^t p_0 q_0 + a_l^s(1 - a_l)^t p_0(1 - q_0)}{a_h^s(1 - a_h)^t p_0 q_0 + a_l^s(1 - a_l)^t(1 - p_0 q_0)}.$$

Simple algebra demonstrates that this holds as long as $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$. ■

Incumbency matters because both the project and the head must be good in order for the unit to be more likely to generate output. The information obtained by the manager from observing the output stream is quite noisy because of the two sources of uncertainty, but if the head and the project have been together for some period, then some of the uncertainty can be eliminated: when computing the joint probability that both are good, the manager computes the product of his *conditional* beliefs about the head's quality and his unconditional beliefs about the project's quality. As long as the output stream has appeared to come from a good project and head, the reduction in uncertainty makes the manager believe that the head is more likely to be of high quality.

The previous two results consider head replacements. Analogous results can be obtained for the case of replacing projects. One of the results tested below can be summarized as follows:

Result 4: Older units receive more resources than new units, holding head characteristics constant.

Proof: Suppose the manager has a head who is believed to be good with probability p , and needs to assign him to a project. The firm has one old project that is believed to be good with probability q_{st} , and a new project. In this case, the expected output is higher with the old project as long as $pq_{st} \geq pq_0$. Using the expression for q_{st} in equation (2.3), simple algebra shows that $q_{st} \geq q_0$ as long as $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$. Note that, by Lemma 1, the condition $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$ is the same one that ensures that the head is not removed and that the project is not shut down. Therefore, older units receive more resources, holding head characteristics constant. ■

The above results suggest that unit resources are positively related to initial indicators of head and project quality, the head's previous experience in R&D, the number of years the head has been head, and the age of the unit. One additional feature of the model that also leads to this relationship is the manager's initial assignments of heads to projects. Suppose there are two heads and two projects, none of which have been together before, and the

manager believes that one head is better than the other and one project is better than the other. How should the heads and projects be matched?

Result 5: If there are two heads and two projects, none of which have been together before, and the manager believes that one head is better than the other and one project is better than the other, the better head is matched with the better project.

Proof: Suppose that the worse head and project are believed to be good with probabilities p and q respectively, and that the better head and project are believed to be good with probabilities $p_1 = \gamma p$ and $q_1 = \mu q$, where $\gamma > 1$ and $\mu > 1$. Since $\gamma > 1$ and $\mu > 1$, $(1 - \gamma)(1 - \mu) > 0$. Expanding and rearranging, $\gamma\mu + 1 > \gamma + \mu$, which implies that $\gamma p \mu q + p q > \gamma p q + p \mu q$, which can be rewritten as $p_1 q_1 + p q > p_1 q + p q_1$. This last inequality implies that expected output is higher if the heads and projects are matched according to their qualities. ■

Result 5 establishes that good heads tend to be matched with good projects. This provides an additional reason why indicators of head quality that can be observed at the time appointment decisions are made should be positively correlated with the amount of resources allocated to the project.

The final result in this subsection considers how removal decisions depend on past experience. Above it was shown that if a new head and a new project are initially paired together, then the retention condition is the same for both. It is of some interest to ask, what if a new head joins an established project? Intuitively, because the project must have had some past successes in order to still exist, whereas the head has had no successes, the manager will always be more likely to believe the head is bad than the project is bad. The next result confirms this.

Result 6: If a new head joins an established project and the unit later performs poorly, the head will always be replaced before the project is shut down, if shut-down occurs.

Proof: Denote the manager's initial belief about the project quality at the time the head and project are matched by q' , where q' must be at least q_0 (otherwise the project would have been shut down). Lemma 1 shows that a new head is removed if and only if $a_h^s(1 - a_h)^t < a_l^s(1 - a_l)^t$. We will show that the project is always kept as long as $a_h^s(1 - a_h)^t \geq$

$a_l^s(1 - a_l)^t$, and may also be kept if $a_h^s(1 - a_h)^t < a_l^s(1 - a_l)^t$, as long as q' is high enough. After s successes and t failures with the new head, the manager keeps the project as long as

$$\Pr\{\text{the project is good given that the head is good}\} p_{st} \geq p_{st} q_0.$$

Substituting in for $\Pr\{\text{the project is good given that the head is good}\}$ and cancelling the p_{st} terms, this inequality can be expressed as

$$\frac{a_h^s(1 - a_h)^t q'}{a_h^s(1 - a_h)^t q' + a_l^s(1 - a_l)^t(1 - q')} \geq q_0$$

This inequality holds as long as $a_h^s(1 - a_h)^t q'(1 - q_0) \geq a_l^s(1 - a_l)^t q_0(1 - q')$. If $q' > q_0$, this inequality is always satisfied when $a_h^s(1 - a_h)^t \geq a_l^s(1 - a_l)^t$, and can be satisfied when $a_h^s(1 - a_h)^t < a_l^s(1 - a_l)^t$ as long as q' is sufficiently greater than q_0 . Therefore, the head must be removed before the project is shut down. ■

Result 6 establishes one reason why the turnover of heads may be higher than the turnover of units. The pattern of head turnover exceeding unit turnover appears in the data discussed below.

2.1. Additional Implications for Cross-Sectional Data

Since the data set used below is a cross section of research units, this subsection discusses some of the model's implications for cross-sectional data. To facilitate the link between the model and the data, it is implicitly assumed that a “unit” in the data has a single “project” as described in the model. That is, the empirical counterpart of the “project” is simply whatever activities the unit undertakes.

The first implication is that older units should be larger on average, and the variance in size should be large among older units. To see this, suppose that at time 0, a group of managers draw new heads and research projects from the same distributions, so the initial beliefs of all managers are p_0 and q_0 . Consider how unit size evolves over time. At time 0, units are allocated resources according to the managers' beliefs about the likelihood that output occurs. Therefore, all units receive the same amount of resources. As managers observe different output over time, they update their beliefs to obtain different values of

λ , which leads to greater variability in size in the cohort. Further, the managers shut down under-performing units and tend to allocate more resources to the units that survive. Therefore, the average size of a unit in terms of resources tends to grow over time, conditional on survival. In a cross section with many age categories, the older units would be larger on average and have more variation in size.

As firms in the data used below are in different countries and different fields, and are surveyed at different points in time, it is unlikely that the managers draw their heads from a common pool. In the data, heads differ by R&D experience and education level. Also, it is possible that firms promote from within, so managers might have some information about their new heads that other firms do not have. Because of this, managers have different priors about the quality of new heads. Since new heads differ, unit size is expected to have more variation than in the case where all managers draw their heads from a common pool. However, the above conclusions about how unit size evolves still apply.

3. Empirical Results

3.1. The Data

The data is from the International Comparative Study on the Management, Productivity, and Effectiveness of Research Teams and Institutions, an international study of research units conducted by UNESCO in the years 1971-89. Research units of various organizations from several countries were surveyed at different points in time, and organizations were surveyed only once (therefore the data is cross-sectional). The types of organizations surveyed includes universities, government research institutions, cooperative research institutions, and firms. For this study, research units belonging to *firms* involved in either agriculture, chemistry, physics, or the technical sciences are selected. The countries represented in the data used here are Austria, Belgium, Brazil, Egypt, Finland, Hungary, Korea, Nigeria, and Spain.

A *research unit* is defined in the survey as the smallest group of persons forming a coherent cell with a recognized leader, having the following characteristics:

1. The unit carries out at least one research project.

2. The unit has at least three *core members* (including the head).
3. The unit has been in existence for at least half a year and has a total expected life span of at least one year.

A *core member* is a person who devotes at least 8 hours per week to the work of the unit and who has communication (direct or indirect) with the unit's head at least once each month. Units are typically small (see Table 1. below).

Theoretical results 1-4 predict that the amount of resources allocated to a head of a research unit depends on indicators of head quality that can be observed at the time he becomes head, his R&D experience, his length of tenure as head, and the age of the unit. Result 5 establishes that unit size is correlated with head quality for another reason as well - heads who are believed to be better are assigned to units that are believed to be better. To investigate these claims empirically, a measure of the resources allocated to the head is required. As labor is an important input in research units, the proxy for resources is the number of scientists in the unit. The following equation is estimated:

$$sci = f(age, educ, exp, yrshead, country/type\ dummies)$$

The dependent variable is *sci* (number of scientists in the unit). The independent variables are *age* (age of the unit), *educ* (years of education of the head), *exp* (years of R&D experience of the head before becoming head of the unit), *yrshead* (number of years the head has been head of the unit), and several country/unit type dummy variables. The country/unit type dummies take the value 1 for specific country/unit types and 0 for all other country/unit types (for example, *finch* equals 1 for research units in chemical firms in Finland and 0 otherwise). Once observations with missing values are excluded there are 245 observations.

Note that, unlike resources in the model, the number of scientists can be expected to influence the likelihood of generating output. However, allowing for this effect in the model would not likely change the results. The model's results rely on two sets of assumptions, the Resources Assumption and the assumptions on *a*. The main content of the Resources Assumption is that a manager allocates more resources to units that he believes are more likely to have good opportunities for generating output because of the quality of the projects

and heads. This is a reasonable assumption even if resources influence the likelihood of generating output. The assumptions on a imply that a manager cannot use resource adjustments to help disentangle the effects of project quality from the effects of head quality. This also seems reasonable. Even if resource adjustments increase the speed of learning about λ , the manager still has to rely on his beliefs to determine whether the project or the head is the problem in a poorly-performing unit. Therefore, while introducing the interactions of resource allocation with the evolution of beliefs into the analysis would allow a variety of additional interesting issues to be explored, it is likely that the conclusions presented above would still be valid.

Summary statistics for the variables used in the regression are given in Table 1. The summary statistics suggest that some type of selection process is operating: both the age of the unit and the years as head distributions are skewed to the right, so most units and heads are relatively new, and few reach old age. Further, most heads are younger than the units that they lead. These facts show that many young units are shut down before they reach old age, and that heads are not identified with the unit, and can leave and arrive while the unit continues to survive. These facts are consistent with Result 6 described above, but there are other possible explanations. Additional explanations for the empirical results obtained here are briefly discussed in the conclusion.

3.2. The Results

The theoretical model suggests that the number of scientists is increasing in the age of the unit, the years of education of the head, the years of R&D experience the head has before becoming head, and the number of years the head has been head. The model does not establish which effects are the most important, and the empirical results shed some light on the relative importance of the various factors.

Two key factors determine the econometric specification. First, since the dependent variable is integer-valued, a count data model is appropriate. Second, since the theoretical model predicts that unit size is more variable in cohorts that have older units and more experienced heads, it is important to allow for cross-section heterogeneity (overdispersion of the number of scientists). The negative binomial count data model (described in detail by

Greene (2000)) is appropriate in such a case. In the negative binomial model, the conditional mean number of scientists is a function of the variables of interest and a unit-specific shock:

$$E(sci_i) = e^{\beta'x_i + \epsilon_i} = \gamma_i u_i,$$

where x_i represents the variables of interest, $\gamma_i = e^{\beta'x_i}$ and $u_i = e^{\epsilon_i}$. Under the assumption that u_i has a gamma distribution with mean 1 and variance α , the density of sci_i conditional on x_i has conditional mean γ_i and conditional variance $\gamma_i(1 + \alpha\gamma_i)$, where α measures overdispersion relative to the Poisson distribution. That is, the Poisson model is exactly like the negative binomial model except that $\alpha = 0$, so it restricts the conditional variance to be the same as the conditional mean, while the negative binomial model allows the conditional variance to be larger. Both OLS and Poisson results are included below for comparison. The OLS model does not take into account the fact the the dependent variable is count data; sci_i is simply regressed on x_i .

Table 2 reports the estimation results for the three models. In 3 country/unit type cases, unit size is perfectly predicted by the country/unit type. These observations are excluded from the estimation routines. All three sets of results suggest that there is a positive relationship between unit size and the four variables of interest. The overdispersion parameter of the negative binomial model, α , is statistically significant at the 1% level, which suggests that there is substantial cross-sectional heterogeneity, and that the restriction to the Poisson model can be rejected. As mentioned above, this is consistent with the way the model predicts unit size to evolve over time.

Since some of the units are fairly large, Table 3 checks the robustness of the results by eliminating units with more than 20 scientists. The results show that the effects of the four variables of interest are still present, but are less pronounced, and the effect of the years of experience of the head is statistically insignificant.

Table 4 reports the estimated marginal effects of the variables of interest on the expected unit size. The results are based on the negative binomial models in Tables 2 and 3. In both cases, the effect of an additional year of education has the largest relationship with unit size, and an additional year as head of the unit has the next largest impact. Roughly, based on the coefficients from Table 2, on average one extra scientist is added if either the head has

4 additional years of education, 7 additional years as head of the unit, 9 additional years of experience before joining the unit, or if the unit is 17 years older.

4. Conclusion

This paper has presented a simple selection model of the determinants of the span of control of the heads of small groups and applied the model to study research units in firms. The test results demonstrate that unit size is positively related to unit age as well as the head's education, R&D experience, and years as head. The selection model offers one explanation for the observed facts: In the model, new heads with high education and previous experience are matched with better units, and better units are larger. Second, the selection dynamics imply that if the unit head remains head, he receives more resources each period than a new head of comparable quality would be able to obtain. Third, older units have been revealed over time to be productive, and as a result are allocated more resources. Finally, the model accounts for the observed overdispersion of unit size - this is a natural outcome when different units receive different output shocks over time.

Although selection dynamics likely play a role in determining unit size, clearly other factors can account for some of the observed patterns in the data. For example, learning by doing could explain why older units and units with longer-serving heads tend to receive more resources. It is difficult to obtain sharp distinctions between a selection model and a learning by doing model given the available data. As noted, the summary statistics suggest that some type of selection process is operating: the facts show that many young units are shut down before they reach old age, and that heads are not identified with the unit, and can leave and arrive while the unit continues to survive. However, these facts cannot establish that the exact selection process outlined in the theoretical model above is responsible for the observed patterns. Employees can enter and leave research units for a variety of reasons including promotions and departures from the firm, and units can be shut down because of external shocks or evolutionary trends in the market that make them no longer required. Further work could explore the impact of these various factors on the span of control of small group heads.

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Table 1. Summary Statistics (245 observations)

Variable	Median	Mean	Std. Dev.	Minimum	Maximum
<i>Number of Scientists</i>	4.00	5.48	6.45	0.00	61.00
<i>Age of the Unit</i>	6.00	10.11	10.49	0.00	57.00
<i>Years of Experience Prior to Becoming Head</i>	6.00	7.76	6.78	0.00	34.00
<i>Years as Head</i>	3.00	5.13	5.59	0.00	38.00
<i>Years of Education</i>	18.00	18.33	2.72	12.00	30.00

Table 2. Determinants of Research Unit Size, as Measured by the Number of Scientists in the Unit (242 observations)

	OLS		Poisson		Negative Binomial Model	
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
<i>constant</i>	-6.36*	3.86	-0.72**	0.31	-0.48	0.61
<i>Age of the Unit</i>	0.071	0.044	0.011***	0.0029	0.011**	0.0047
<i>Years of Education</i>	0.30**	0.15	0.058***	0.011	0.051**	0.023
<i>Years of Experience</i>	0.11*	0.062	0.020***	0.0043	0.021**	0.0094
<i>Years as Head</i>	0.21**	0.085	0.036***	0.0052	0.028***	0.0072
<i>auste</i>	3.90*	2.32	0.88***	0.21	0.80*	0.42
<i>belte</i>	3.70	2.68	0.81***	0.22	0.72*	0.42
<i>brach</i>	1.29	4.21	0.27	0.40	0.19	1.09
<i>braph</i>	3.51	3.10	0.82***	0.26	0.76	0.53
<i>brate</i>	2.95	2.64	0.68***	0.24	0.63	0.49
<i>finag</i>	2.50	2.83	0.51**	0.25	0.60	0.46
<i>finch</i>	2.40	2.68	0.56**	0.24	0.47	0.46
<i>finph</i>	12.15**	4.82	1.76***	0.28	1.73***	0.66
<i>finte</i>	5.66**	2.61	1.22***	0.23	1.11***	0.43
<i>hunag</i>	3.50	3.81	0.84***	0.30	0.80	0.57
<i>hunch</i>	8.50***	3.24	1.52***	0.24	1.44***	0.48
<i>hunph</i>	16.91***	4.82	1.98***	0.26	1.79***	0.53
<i>hunte</i>	2.28	4.87	0.38	0.49	0.27	6.57
<i>korch</i>	6.08	4.89	1.31***	0.37	1.19	1.31
<i>korph</i>	6.90*	4.24	1.45***	0.32	1.31	1.16
<i>korte</i>	7.05*	3.83	1.47***	0.29	1.34	0.85
<i>nigte</i>	7.46	4.84	1.44***	0.32	1.40**	0.66
<i>spach</i>	2.32	2.93	0.59**	0.26	0.49	0.49
<i>spaph</i>	2.73	3.73	0.70**	0.31	0.65	0.87
<i>spate</i>	1.84	2.39	0.43**	0.22	0.38	0.42
<i>alpha</i>	-	-	-	-	0.31***	0.047
R-squared	0.18		-		-	
Log Likelihood	-766.68		-755.96		-611.27	
Restricted Log Likelihood	-791.35		-901.54		-755.96	

The country/unit-type dummies are constructed as follows: Countries are coded by the first three letters in their names, and unit type is coded by the first two letters. The countries are Austria, Belgium, Brazil, Finland, Hungary, Korea, Nigeria, and Spain. The unit types are agriculture, chemistry, physics, and technical.

alpha is the overdispersion parameter of the negative binomial model (Greene (2000)).

* Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level.

Table 3. Determinants of Research Unit Size, as Measured by the Number of Scientists in the Unit, Including only Units with 20 or fewer scientists (232 observations)

	OLS		Poisson		Negative Binomial Model	
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
<i>constant</i>	-1.42	1.92	0.062	0.33	0.14	0.39
<i>Age of the Unit</i>	0.057***	0.022	0.012***	0.0032	0.011***	0.0035
<i>Years of Education</i>	0.14*	0.076	0.032***	0.012	0.029**	0.015
<i>Years of Experience</i>	0.043	0.031	0.0088*	0.0048	0.0088	0.0069
<i>Years as Head</i>	0.069	0.045	0.018***	0.0068	0.019**	0.0077
<i>auste</i>	2.09*	1.15	0.55***	0.21	0.53**	0.27
<i>belte</i>	1.69	1.33	0.46**	0.24	0.48*	0.27
<i>brach</i>	0.75	2.08	0.20	0.40	0.19	0.83
<i>braph</i>	2.72*	1.53	0.70***	0.26	0.69**	0.35
<i>brate</i>	2.05	1.30	0.55**	0.24	0.53	0.33
<i>finag</i>	1.98	1.40	0.50**	0.25	0.52*	0.30
<i>finch</i>	1.74	1.32	0.47**	0.24	0.44	0.29
<i>finte</i>	3.43*	1.30	0.85***	0.23	0.83***	0.29
<i>hunag</i>	2.92	1.88	0.75**	0.31	0.74*	0.40
<i>hunch</i>	4.92***	1.66	1.07***	0.26	1.04***	0.38
<i>hunte</i>	0.95	2.40	0.17	0.50	0.14	2.51
<i>korch</i>	4.26*	2.41	1.04***	0.37	1.01	0.80
<i>korph</i>	5.10**	2.09	1.18***	0.32	1.15*	0.67
<i>korte</i>	5.23*	1.89	1.20***	0.29	1.17**	0.50
<i>nigte</i>	6.54*	2.38	1.30***	0.32	1.30***	0.40
<i>spach</i>	1.89	1.44	0.52**	0.26	0.47	0.31
<i>spaph</i>	2.26	1.84	0.60**	0.31	0.58	0.53
<i>spate</i>	0.90	1.18	0.24	0.22	0.22	0.27
<i>alpha</i>	-	-	-	-	0.12***	0.034
R-squared	0.17		-		-	
Log Likelihood	-571.13		-539.16		-523.01	
Restricted Log Likelihood	-592.29		-580.13		-539.16	

The country/unit-type dummies are constructed as follows: Countries are coded by the first three letters in their names, and unit type is coded by the first two letters. The countries are Austria, Belgium, Brazil, Finland, Hungary, Korea, Nigeria, and Spain. The unit types are agriculture, chemistry, physics, and technical.

alpha is the overdispersion parameter of the negative binomial model (Greene (2000)).

* Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level.

Table 4. Marginal Effects of the Determinants of the Span of Control of the Head, Computed at the Mean Values

	Based on Table 1		Based on Table 2	
Marginal Effect	Coefficient	Std. Error	Coefficient	Std. Error
<i>Age of the Unit</i>	0.060**	0.028	0.047***	0.016
<i>Years of Education</i>	0.27**	0.14	0.13**	0.068
<i>Years of Experience of the Head</i>	0.11**	0.056	0.039	0.032
<i>Years as Head of the Unit</i>	0.15***	0.043	0.083**	0.036
<i>Conditional Mean Number of Scientists</i>	5.36	-	4.44	-

* Significant at the 10% level ** Significant at the 5% level *** Significant at the 1% level.