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The bureaucratization of science

John P. Walsh*, You-Na Lee

Georgia Institute of Technology, United States

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ABSTRACT

While science is traditionally treated as a distinct domain of work organization, increasingly science is organized around larger and larger work groups that resemble small firms, with knowledge as the product. The growth of organized science raises the question of whether we also see a bureaucratic structuring of scientific work groups as predicted by organization theory, with implications for the academic credit system and scientific labor markets. Building on organization theory, we examine the relation between project group size, technical environment, and bureaucratic structuring of scientific work. Using survey data on scientific projects, we find size predicts bureaucratic structuring, with declining marginal effects. We also find that interdisciplinarity and task interdependence have distinct effects on bureaucratic structuring. Finally, the relationship between size and some dimensions of bureaucratic structuring is contingent on levels of work group interdependence in the field. We conclude with a discussion of the implications for policy debates about authorship and scientific careers.

1. Introduction

"Secretaries post off papers from the laboratory at an average rate of one every ten days. However, far from being reports of what has been produced in the factory, members take these papers to be the product of their unusual factory." (Latour and Woolgar, 1979:47).

Science is increasingly becoming a team activity (Wuchty et al., 2007). While this trend began decades ago (Price, 1963; Swatez, 1966), the sizes of contemporary research teams in many fields are beginning to approach that of medium-sized firms (Biagioli, 2003; Birnholtz, 2006; Milojević, 2014; Pavlidis et al., 2014; Salonius, 2008). Rather than a focus on an individual's lab bench, scientific work increasingly takes place in a setting that more closely resembles a small "factory" or "quasi-firm", run by a "small businessperson" lab director (Etzkowitz, 1983; Hackett, 1990; Latour and Woolgar, 1979; Shrum et al., 2007). This growth in the size of scientific work teams raises the question of the impact of size on the organization of scientific work (Carayol and Matt, 2004; Chompalov et al., 2001; Swatez, 1966). We extend prior work on the organization of science by examining the internal organization of scientific projects, in particular how the structuring of research projects varies by size and environmental context, building on the classic sociology of organization structures (Blau, 1970; Child, 1973; Meyer, 1972; Pugh et al., 1968).

We argue larger research teams are associated with more bureaucratic structuring of the team: greater division of labor, standardization, hierarchy and decentralization. Furthermore, project scope and team interdependence also affect bureaucratic structuring. Finally, the size–structure relation is contingent on the level of interdependence in the research team.

In addition to developing the sociology and economics of science, this work also tests the utility of organization theory for explaining the structures of self-organizing groups of professionals, and by examining the effects of size at modest group sizes (with the bulk of the projects having on the order of 5–10 people), to see how sensitive these size–structure relationships are across even a modest size range.

Two key insights drive this discussion. First, a scientific project is not a point mass, but consists of a group of members organized along a variety of dimension (Barley and Bechky, 1994; Carayol and Matt, 2004; Chompalov et al., 2001). And, this internal structure may be critical to performance (Andrews, 1976; Carayol and Matt, 2004; Cummings et al., 2013; Fox and Mohapatra, 2007; Hollingsworth, 2009). Secondly, science is not science. Fields differ significantly in their structure and dependencies (Collins, 1975; Fuchs, 1992; Hargens, 1975; Whitley, 1984). Therefore, we examine the internal structure of scientific projects, and the environmental contexts in which these structures operate.

In the following sections, we discuss the changing nature of scientific work, use organization theory to generate hypotheses about

* Corresponding author.
E-mail addresses: jpwalsh@gatech.edu (J.P. Walsh), youna.lee@gatech.edu (Y.-N. Lee).

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the structural implications of these changes, test these hypotheses using recently collected data from a broad sample of research projects across scientific fields, and then conclude with a discussion of the implications of these findings for the sociology and economics of science: in particular, training, careers, and the reward structure in science.

2. The growth of organized science

While science being conducting in organizations (such as universities, government labs, and industry labs) is not a new phenomenon (Blau, 1994; Pelz and Andrews, 1976), we are observing a fundamental change in the organization of individual research projects. While traditionally science is seen as an individual endeavor (Hagstrom, 1964; Shrum et al., 2007), increasingly scientific projects are group activities, and the groups are growing larger (Adams et al., 2005; Wuchty et al., 2007). While high-energy experimental physics is the extreme example, it is not rare to find research labs with dozens of members and research papers with 10 or more authors. For example, Wuchty et al. (2007) show the rise in the number of authors per paper over the last 40 years, with mean group size in science and engineering nearly doubling over this period. Similarly, Adams et al. (2005) find an increase in co-authored papers, in the number of authors per paper, in papers spanning institutions, and in international collaborations.

3. Size, interdisciplinarity, technology, and the bureaucratization of scientific work

This work on the relation between size and structure begins with Weber's classic analysis of the characteristics of bureaucratic organization (in contrast to paternalistic or collegial organization), which emphasizes the importance of division of labor, formalization and standardization, hierarchy and decentralization, as well as specialized competence and internal careers, among other aspects of the ideal-type bureaucracy (Weber, 1978). Weber (1978) notes that bureaucratization is associated with increasing size and scope of the organization.

3.1. Bureaucracy as a multidimensional concept

Bureaucracy is a multidimensional construct. While each of these dimensions is correlated, they are formally distinct, and a particular organization can be high on one dimension while low on another (Hall, 1962; Pugh et al., 1968). These dimensions include (with the labels varying across studies): Division of Labor/Specialization/Complexity; Standardization/Formalization; Hierarchy/Vertical span; Supervisory intensity/Span of control/Configuration; and Decentralization (Hage and Aiken, 1967; Hall, 1963; Pugh et al., 1968). By division of labor, this literature on bureaucratization means the extent to which the tasks in the organization are divided into stable bundles. By standardization, they mean the extent to which the process for executing those tasks is specified. Hierarchy means the extent to which there are multiple levels of appeal and supervision (i.e., formally ranked lines of reporting). And, finally, centralization/decentralization means the extent to which those lower in the hierarchy can make independent decisions (discretion), even if those decisions may have to be formally approved by those higher in the organization and the extent to which they participate in the decision-making overall (participation). Thus, "bureaucratization" is the extent to which a particular structure is high on each of these dimensions.

3.2. Size

This program of systematizing empirical studies of organization structures produced a series of studies that found size a key driver of structure (Blau, 1970; Child, 1973; Meyer, 1972). These studies have important implications for the work of science as research group size increases. As scientific activity increasingly becomes organized into multi-member projects, the sociology and economics of science also need to take into account the more organized nature of scientific work.

Prior studies of research units (labs, departments, universities) mostly focus on the relationship between size of research units and their performance. For example, there is some evidence that research productivity increases with unit size (Cummings et al., 2013; Johnston, 1994; Stankiewicz, 1979; Wallmark et al., 1973) while evidence by Cohen (1980, 1981) and Seglen and Aksnes (2000) shows that productivity (i.e., publication rate per capita) is independent of unit size. Similarly, Blau (1994) finds a large positive correlation between size of the academic institution and publication productivity per faculty, but that effect becomes not significant after controlling for research focus, reputation, and other university characteristics. Qurashi (1984, 1993) compares the relative publication rate per person across successive size ranges and finds a non-monotonic relation. There is also contrary evidence showing a negative relationship between size and productivity (Bonaccorsi and Daraio, 2005; Carayol and Matt, 2004; Mairesse and Turner, 2005). Horta and Lacy (2011) find a positive relationship between research unit size and international publications, but a negative relationship between size and national publications, and no relation between size and overall productivity.

While the main focus of this prior research is the direct relation between size and productivity, these studies point to the need to examine the team-level structures that are associated with increased size and that might predict outcomes, such as productivity or creativity (Carayol and Matt, 2004). This prior work argues that as size increases, a research group might face coordination difficulties, and hence, we should find the research groups having more decentralization of decision making and greater division of labor, becoming more bureaucratically structured (Bonaccorsi and Daraio, 2005; Cohen, 1980; Johnston, 1994; Kretschmer, 1985; Wallmark et al., 1973). Although this change in scientific teams may generate analogies between manufacturing and science as production of knowledge, knowledge, not products, is still the main goal of science (Bonaccorsi and Daraio, 2005; Wallmark et al., 1973), and so it is an open question whether scientific work groups will also become more bureaucratically structured as size increases.

Our goal is to examine the extent to which scientific work becomes increasingly bureaucratically structured as size increases. Here we are concerned with the bureaucratization of the scientific research tasks themselves. There may be additional bureaucratic procedures related to interacting with university administration (Blau, 1994) or funding agency reporting requirements, for example, that are outside the scope of our analysis (e.g., procedures related to hiring decisions, institutional review boards [IRBs], export control compliance documentation, procurement procedures, progress reporting requirements, etc.).[1] In other words, we are focusing on the "production" aspects of science (Dewar and Hage, 1978).

As size increases, there are potential productivity gains from division of labor (Becker and Murphy, 1992; Blau, 1970; Smith,

[1] For example, Blau (1994) notes that faculty productivity (publications per capita) is positively associated with decentralization of faculty appointment decision-making (with department faculty influence having a positive effect and dean influence having a negative effect).

1776). We might expect this for scientific organizations, as collaborators specialize in particular aspects of the research task, for example, having some concentrate on data collection (with further subdivision into specific aspects of data collection), others on statistical analysis, and still others on integrating findings into a research report (Shibayama et al., 2015). However, while there may be productivity gains from division of labor, Leahey and Reikowsky (2008) find that only 11% of collaborations in sociology involves complementary specialists (which tend to involve a clear division of labor), while the majority involves cooperation among generalists with little clear division of labor. Similarly, Shibayama et al. (2015) find significant variation in division of labor across life science research labs. One counter force limiting the division of labor is the training function that university research groups perform (for graduate students and post-docs), which may put limits on division of labor (Delamont and Atkinson, 2001; Hackett, 1990; Pavlidis et al., 2014). These findings and arguments suggest that division of labor is not a necessary condition of team research (and hence it is an open question as to what drives this variation in division of labor).

At the same time, increasing size makes direct supervision less viable, and leads to greater need for standardization and formalization of procedures as forms of control (Bendix, 1956; Blau, 1970; Child, 1973). For example, multi-site biomedical studies often need to develop very elaborate data collection protocols in order to ensure comparability of data across many physicians, often spread across multiple facilities, preventing direct supervision (Fisher, 2009). In some fields, this need for coordination can also generate new occupations that specialize in these coordination functions, for example, the specialty of lab manager or clinical trial coordinator (Fisher, 2009; Hendren, 2014). At the same time, increasing burden on supervisors should dampen the increase in the division of labor (Blau, 1970; Child, 1973). For example, once the lab's size is measured in dozens, it may be difficult for a principal investigator to closely supervise all of the graduate students, or even post-docs, in her research group, limiting the ability to further subdivide the tasks. This should be especially true if this would require close coordination to ensure that tightly integrated tasks flow smoothly from one specialized researcher to another (Becker and Murphy, 1992; Van de Ven et al., 1976). Below we discuss this further. These arguments suggest that increasing size should be associated with increasing division of labor and increasing standardization and formalization, but at a decreasing rate (Blau, 1970).

Increased size may also be associated with increasing decentralization of decision-making (Pugh et al., 1968; Weber, 1978). Weber argues that large, bureaucratized structures are associated with greater discretion for the officeholder to execute the functions of the office by application of general rules to the facts of the case (Weber, 1978). Armandi and Mills (1982) find that larger size is associated with greater decentralization (see also Hall, 1963). For the case of colleges and universities, Blau (1994) finds that size is associated with greater decentralization (e.g., greater faculty influence in choosing new faculty), and that more centralized organization is associated with more "paternalistic" (rather than bureaucratic) structuring.

Empirical work on professional organizations suggests some support for these arguments, but also suggests that the size-bureaucratic structuring relationship is still an open question in highly-skilled professional and craft occupations. In a study of high-tech startups in Silicon Valley, Baron et al. (1999b) find that bureaucracy (measured as administrative overhead) is positively, significantly related to size, with a declining marginal effect. They also find that initial size and employment growth are associated with formalization and division of labor (Baron et al., 1999a). In a study of medical practices, Kralewski et al. (1985) find that size and division of labor increase subdivisions, hierarchy, and formalization. However, increasing division of labor need not necessarily lead to other components of bureaucratic structuring. Hagstrom (1964) argues that even in group projects, hierarchy is not the norm in scientific work. Hage and Aiken (1967), discussing professional workers, and Stinchcombe (1959), discussing craft workers, both argue that highly-developed divisions of labor can be organized with minimal standardization or hierarchy. The question then is whether large scientific work teams maintain their professional/craft structure or are more bureaucratically structured (with more standardization and formalization and more hierarchy in addition to greater division of labor and decentralization). Dewar and Hage (1978) argue that high skill specialties, such as those found among university personnel, are inherently not decomposable, and so size should not affect vertical differentiation substantially, especially if we limit our focus to the production aspect (i.e., excluding proliferation of administrative specialties). Looking at this issue in the 1960s and 1970s, Hagstrom (1964) and Hargens (1975) showed that science in their era was still organized more on craft than on bureaucratic industrial principles. However, the question of the decomposability of academic specialties is in part a technical and in part an organizational and sociological issue, and prior work on the transformation of skilled crafts suggests that we should not assume a fully integrated scientist is a fundamental unit (More, 1980; Walsh, 1989). If scientific work is, in fact, becoming decomposable, then we may see increasing size leading also to the vertical (as well as horizontal) differentiation of the scientist role (adding technicians and staff scientists specializing in certain components of the bundle of tasks involved in scientific work) and therefore we would expect size to be associated with hierarchy, as well as division of labor, in contrast to the findings of Dewar and Hage (1978).

Thus, we argue that for larger scientific teams, the degree of division of labor, standardization, hierarchy and decentralization should all be greater. These studies suggest our first hypothesis:

Hypothesis 1. Greater project size increases bureaucratization (division of labor, standardization, hierarchy, and decentralization) of scientific work.

Furthermore, as argued above, larger size should be associated with greater division of labor at a decreasing rate (Blau, 1970).

3.3. Scope

In their study of bureaucratization of physician practices, Kralewski et al. (1985) find that in addition to size, the diversity of the practice, in terms of specialties, is also associated with hierarchy and with division of labor (subdivisions), but not with standardization (perhaps because of offsetting requirements for standardization and flexibility in the face of multiple specialties working together). We should see similar effects of interdisciplinarity as a measure of scope. Similarly, Hollingsworth (2004) argues that increasing diversity in research institutes or universities leads to more division of labor, hierarchy, and standardization. Dewar and Hage (1978) also find that changes in division of labor are driven primarily by changes in scope. Thus, more interdisciplinary research groups (which represent greater scope) should find greater need for administrative coordination and division of labor (Weber, 1978), although not for standardization (because generating rules that fit across disciplines may be difficult). On the other hand, Fuchs (1992) argues that heterogeneity in scientific fields reduces bureaucratization, at the level of the field. Thus, although there is some uncertainty in the predicted effects of interdisciplinarity, this prior work suggests the following hypothesis:

Hypothesis 2. Interdisciplinarity increases division of labor and hierarchy.

Note that interdisciplinarity (meaning, teams composed of researchers trained in different disciplines) does not by definition imply division of labor in project tasks. For example, a physicist and a sociologist may work together to co-develop a model of network dynamics, or a biologist and a physicist and a mathematician may co-develop a new method of sequencing DNA, in each case with all members of the project team sharing the same task set. Thus, it is an empirical question whether interdisciplinarity predicts division of labor and hierarchy as predicted by organization theory. As it is an open question as to the effects of scope on standardization and decentralization, we will examine these as well.

3.4. Technology of production

Building on prior work on the effects of technology and technical systems of production (Scott, 1990; Sproull and Goodman, 1990; Woodward, 1965), we argue that bureaucratic structuring may be contingent on the technology and work organization of a particular field (Fuchs, 1992; Sproull and Goodman, 1990; Whitley, 1984), in particular the level of task interdependence (Thompson, 1967; Van de Ven et al., 1976).

Prior work in organization theory argues that a key driver of structure is the technology of production (Burns and Stalker, 1961; Perrow, 1967; Thompson, 1967; Van de Ven et al., 1976). By technology of production, they mean the organization of the work (e.g., batch, assembly line, continuous process) and degree of uncertainty, analyzability and interdependence in the tasks. These technology effects are net of the size effects discussed above (Van de Ven et al., 1976; Woodward, 1965). Perrow (1967) argues that the uncertainty and the analyzability of the production process are key components of the technology of production. For example, Woodward (1965) compares industrial firms across a large number of industries and finds that they can be classified as small batch, large batch/assembly, or continuous/automated production, based on the uncertainty, the length of runs, the complexity, and the skill needed to handle the production equipment. She then shows that these differences in technology are associated with differences in the structuring of the plant, in terms of division of labor, standardization and hierarchy. Similarly, Van de Ven et al. (1976) show that the use of various coordination mechanisms varies by uncertainty, with more intensive personal and group coordination substituting for impersonal communication (standardization through rules and plans) as uncertainty increases. Marsh and Mannari (1981) argue that both size and technology are critical drivers of structure and we should account for both when predicting observed structures. They find, for example, that size is more dominant for division of labor and formalization and technology is more dominant for administrative overhead. Similarly, Child (1973) finds industry differences in the levels of bureaucratization, net of size and argues that industry is likely a proxy for other variables related to technology of production and environmental uncertainty (see also Lawrence and Lorsch, 1967; Woodward, 1965).

This technology and structure perspective can also be applied to scientific work groups, where the technology of production will vary by field (Collins, 1975; Fuchs, 1992; Hargens, 1975; Shinn, 1982; Whitley, 1984). For example, Fuchs (1992) and Collins (1975) argue that task uncertainty and interdependence in a field should affect the structuring of the field (e.g., craft, collegial profession, bureaucracy). Note that Fuchs and Collins are arguing at the level of the organization of the field, not the individual research project. However, we may still see project-level effects that are similarly related to field-level characteristics, such as technology of production and the degree to which routines are codified into standardized equipment. For example, while so-called home-brew DNA sequencing may have required a researcher with a broad set of skills, who would also engage in multiple other tasks in the project, the development of standardized gene sequencing machines may allow for a technician to specialize in this one task, increasing the division of labor (Barley, 1990; Rogers, 2012). Using this perspective, Shinn (1982) compares the organization of research groups in mineral chemistry, solid-state physics and computerized vector analysis and argues that the instruments, techniques, and production processes (degree of repetition and of uncertainty) drive the structuring of work in different fields. For example, Shinn describes the work in the mineral chemistry labs as involving a large variety of instruments, each of which might be used for testing the same chemical for different properties, and a high degree of repetition and low uncertainty, all of which lead to division of labor; a sharp divide between the labor intensive work and the higher-level cognitive work needed to plan and interpret experiments, which leads to hierarchy; and also a moderately high level of interdependence (serial or reciprocal) in all these tasks, which requires significant coordination (see below). In contrast to the standardized instruments of the chemical labs, the operation of customized and highly fickle instruments in the physics labs, as well as the nuanced interpretation of the outputs required, leads to much more fluidity in the roles in these experiments (less division of labor and less hierarchy). And, in the computerized vector analysis labs, the primary technology is pencil and paper, supplemented by an automated computer (a much less labor intensive instrument). Following Burns and Stalker (1961), Shinn (1982) suggests that the more bureaucratic structure in mineral chemistry, and the more organic structure in computerized vector analysis (and the intermediate structure in solid state physics) can be partly explained by such differences in the technology of production. Similarly Hargens (1975) shows how chemistry, political science and mathematics vary in terms of routineness in the technology of production (similar to Perrow's uncertainty and analyzability) and finds that the structuring of research groups (for example, division of labor) is associated with routineness.

Thus, based on this prior work, we argue that field differences in part represent differences in the technology of production that contingency theory argues should affect the underlying tendencies toward more or less bureaucratic structuring. We will use field-level fixed effects as a proxy for the underlying technology of production (Child, 1973; Collins, 1975; Fuchs, 1992; Shinn, 1982; Whitley, 1984).

3.5. Interdependence

In addition to uncertainty and analyzability, prior work suggests that the structuring of scientific work may be conditioned on the interdependence of tasks in the project (Hargens, 1975). Van de Ven et al. (1976) define interdependence as the extent to which unit members are immediately dependent upon one another to perform their individual jobs (see also Mohr, 1971; Thompson, 1967). Building on Thompson (1967), Van de Ven et al. (1976) describe different forms of interdependence, from pooled, to serial, to reciprocal, to team, with each representing a greater degree of interdependence. They find that increasing interdependence is associated with greater use of personal and especially group coordination mechanisms, and declining use of impersonal rules and plans, because of the greater demands for coordination in a highly interdependent workflow. Walsh and Maloney (2007) find that within scientific collaborations, greater interdependence is associated with greater problems with coordination. Whitley (1984) argues that interdependence (across projects in a field) is a key factor driving the overall level of bureaucratic structuring of fields (especially hierarchy and standardization). We argue that this may affect bureaucratic structuring within projects as well (Chompalov et al., 2001; Hargens, 1975). Software development project teams, especially during the final stages, are often highly interdependent

(Teasley et al., 2000). A space physics research team tracking an upper atmospheric event is another example of what Van de Ven et al. call "team interdependence", requiring simultaneous coordination and responsiveness to each other's decisions and actions (Finholt, 2002). Co-authors passing back and forth drafts of a paper, or of a survey instrument, is an example of reciprocal interdependence, as is the interaction between someone doing the analysis and another person interpreting the results and suggesting the following analysis (Shinn, 1982). Some assays in biology that involve multiple members working in a tightly linked series is an example of serial interdependence: such as one member extracting materials from a cell, another preparing the slides before the sample decays, and a third focusing the electron microscope to view the slide and interpret the results. In contrast, when interdependence is low, perhaps through decoupling and time buffering of tasks (Thompson, 1967; Van de Ven et al., 1976), there may be less need for tight control and coordination, even in relatively large groups. For example, in an archeological or paleontology dig, the members spread out over the site, and each does her part, carefully, but with little need for coordination and communication. And, when any member finds something, the results are added to the data (pooled interdependence, in Van de Ven's terminology). The Human Genome Project may be an extreme example of this pooled interdependence, with each researcher working on a particular part of the genome and posting sequences to the shared database as they are completed (Shreve, 2004). Crowd sourcing science (the fold.it protein folding project, for example) is another example. In each of these cases of pooled interdependence, adding additional members to the team does not lead to a more bureaucratized structure. Note that interdependence is not conditioned on division of labor. For example, two mathematicians jointly working on a problem will have high interdependence but little or no division of labor (Hagstrom, 1964). Similarly, workers in a stamping plant (or in Adam Smith's archetypical pin factory) may have low (or high) specialization, but moderate interdependence (if there are sufficient buffers between workstations), but adding automated transfer between stations increases the interdependence among workers, without changing the division of labor, because of the greater need for moment by moment coordination (see Zetka, 1992). Similarly, Perlow (1999) found that local collaborations among engineers developed increasingly tight-linked interdependencies that tended to reduce productivity. A field experiment showed that reducing the level of interdependence, while still keeping the same division of labor and maintaining procedures for sharing information and joint problem solving, increased productivity.

Based on prior work in organization theory and economics, we would expect that greater interdependence would have mixed effects on the different components of bureaucratic structuring. These relations are largely driven by the increasing needs for coordination created by greater interdependence in the work flows (Van de Ven et al., 1976). For example, Van de Ven et al. (1976) find that greater interdependence (reciprocal or team vs. pooled) is associated with greater use of horizontal communication and group meetings and less use of plans and rules (so that some aspects of standardization/formalization should be less, while others, involving personal coordination mechanisms, may be greater). Becker and Murphy (1992) argue that the need for coordination is one factor that limits division of labor, suggesting that greater interdependence should, ceteris paribus, be associated with less division of labor. Considering the other components of bureaucratic structuring, based on Van de Ven et al. (1976), the effects on hierarchy, in the sense of vertical over horizontal communication, should be negative, although hierarchy as the existence of managerial layers may be unaffected. Teasley et al. (2000) show that software development teams are more productive when radically collocated (war rooms), because such radical collocation facilitates non-hierarchical, non-standardized, real-time communication. As for decentralization, following Weber, to the extent that decentralization means discretion (ability of front line workers to make autonomous decisions, based on rules and authority of their position), this should be lower, because of greater need to coordinate the decision-making of all of the interdependent front-line members. These arguments suggest the following hypotheses about the relation between interdependence and bureaucratic structuring.

Hypothesis 3. More interdependence is associated with (a) less division of labor; (b) more (interpersonal) standardization; (c) less hierarchy (use of vertical over horizontal communication channels); and (d) less decentralization (discretion to make independent decisions).

3.6. Size–interdependence interaction

In addition to these main effects of interdependence on bureaucratic structuring, Fuchs (1992) argues that the size-bureaucratization link is contingent on interdependence. In particular, when interdependence is high, then the overall structure of the project is more closely linked, and hence the structuring of the project may respond more to size (Hargens, 1975). We can think of the contrast between a low interdependence archeological dig (where adding additional people will not change the level of standardization or division of labor or hierarchy) and a high interdependence physics or chemistry experiment, where team size may more strongly influence the bureaucratic structuring of the work (net of the sometimes offsetting main effects of size and of interdependence). Thus, we argue that the relation between size and bureaucratic structuring will be stronger in high interdependence fields.

Hypothesis 4. In science fields with high interdependence, the effect of project size on bureaucratic structuring is larger than in fields with low interdependence.

We will categorize fields as having high or low interdependence to test the main and interaction effects of interdependence (Mohr, 1971; Van de Ven et al., 1976).

In addition to project size, interdisciplinarity, interdependence, and the contingency effect of project size by interdependence, there may be other contextual factors that predict bureaucratization (Collins, 1975; Fuchs, 1992; Whitley, 1984). For example, private research organizations may have more organizational flexibility than public organizations. Also, larger organizations should be more bureaucratic (see also Cullen et al., 1986). For example, Blau (1994) finds, for colleges and universities, size is associated with greater division of labor (using number of academic departments as the measure of division of labor) and more levels of hierarchy. Therefore, we will also control for organizational size and being public vs. private.

4. Data and methods

To test these questions requires information from a large sample of projects spanning fields and institution types. We will use data from a survey of scientists in the US. The population of interest is scientific projects in the fields of science covered by the Web of Science. Here, field is defined by the field of the journal where the paper is published, as defined by the ISI classification (classified into 22 fields covering all ISI science and social science journals, see Appendix A). This definition allows us to test the effects of interdisciplinary projects separately from the field of the published paper (as the field of the paper is defined by the journal in which the results were published, while project scope [interdisciplinarity] is defined by the field composition of the team that produced the result). The survey began with a random sample of over 9000 published papers, covering publication years 2001–2006, stratified by field (all 22 fields in the primary classification) and by forward citations, with an oversampling of the papers in the top 1% of citations in each field in each year (citation counts retrieved December 31, 2006). About 3000 of the sampled papers were in the top cited papers and about 6000 were from other random papers.

The list of papers was searched for an appropriate contact author, beginning with the reprint author, followed by the first or last author (depending on the name ordering conventions in that field), and then going through the list of authors to find a US author for whom a current address (email or, if none available, post mail) could be found. In about 80% of cases, the target author was either the contact author or the first or last author. In cases where no valid contact was available (for example, the author was deceased, or had moved out of the country), we excluded those cases from the sample. Furthermore, to reduce respondent burden, for those scientists that appeared more than once in our sample, we randomly sampled one paper, giving priority to the top-cited papers. In the end, we contacted 8864 target authors (one per paper), with 2327 responses (26% response rate). These 2327 will henceforth be referred to as "respondents".[2] For this analysis, we will limit responses to those in universities and hospitals with at least two members in the research project (N = 1223). We use survey data estimation methods to control for the differential sampling and response rates between top and random papers and across fields. The weights are based on the overall population of published papers, so that weighted means account for the underlying population distributions on field and top v. random papers (Kalton, 1983). All statistics are estimated taking into account the sampling structure and weights (Lee et al., 1989). Furthermore, standard errors for subpopulation (i.e., those with at least two members) statistics are estimated using information from the full sample (West et al., 2008).

To simplify the presentation of results and to ensure sufficient N in each field for estimating accounting for survey strata, we aggregate the fields into 10 categories. Appendix A gives the list of fields, both for 22 disaggregated and 10 aggregate fields.

The survey asked the respondent to describe the research project that produced the sampled paper (which was named on the cover of the survey). This strategy allows us to link bibliometric, survey and institutional data. The survey questionnaire covered such topics as: motivations for the research project; uncertainty; competition; sources of information; organization of the project; project size; composition of the project team (field, gender, national origin, sector, rank); outputs of the project (including patents, licenses, startups); and demographics and education of the respondent.[3]

4.1. Dependent variables

Based on prior literature, bureaucratization is a multidimensional concept (Pugh et al., 1968). Therefore, we create measures of several dimensions of bureaucratization building off this prior work and will test the effects of size on each separately (Blau, 1970; Child, 1973; Pugh et al., 1968). For these measures, we use dummy coding (see Appendix B for original wording of questions, answer scales and recodings) and highlight these results because we are interested in seeing if these bureaucratic practices exist at all in the project. But, as a robustness check, we also test models using ordinal measures to see if size also predicts the extent of implementation of each bureaucratic practice.

4.1.1. Division of labor

We have three binary measures of division of labor: within-lab division of labor, cross-lab division of labor, and existence of specialist roles (technicians), from the Scientist Survey.

Internal DoL: "The project involved a strict division of labor with each person responsible for a specific part of the research."

External DoL: "The project involved outsourcing parts of the work to other research groups."

Specialist role (anytech): "The project included non-author technicians in the research group."

4.1.2. Standardization/formalization

We have two binary measures of standardization:

Regular check: "The project leaders checked the graduate students' lab notebooks at least once per week."

Regular meeting: "The whole research group met every week to share information on project progress."

We argue that these variables measure the extent to which the work of the researchers is expected to adhere to a standard protocol and schedule (although we discuss alternative interpretations in the conclusion). Aiken and Hage (1966) measure two aspects of standardization/formalization, including job codification and rule observation. The first may be less relevant in a setting where each project may need a new set of protocols. Hence, we use the second dimension. Our measure is related to the Aiken and Hage (1966) measures of rule observation: "The employees are constantly being checked on for rule violations" and "People here feel as though they are constantly being watched, to see that they obey all the rules." Pugh et al. (1968) use similar measures of regular supervision for standardization.

4.1.3. Hierarchy

We have a binary measure of hierarchy:

Hierarchical reporting: "There was a clear hierarchy in the research group, such that students reported to team leaders and team leaders reported to lab heads."

We also have another measure of hierarchy based on prior work by Blau (1970), which defines hierarchy as levels of administration. Organizations with management are more hierarchical than those without distinct management roles. Furthermore, in the traditional image of an autonomous scientist working under her own direction, members of scientific work teams are generally considered to be self-managed (Hagstrom, 1964). Therefore, the existence of management in the scientific work team can be a measure of hierarchy. We asked the respondents to report their management role in the project, with the responses: (a) "a leading role in the research management, designing the research project, organizing the research team, and/or acquiring research funds (Principal Investigator or Co-PI)"; (b) "A member of the research management but less than that of the leader" (c) "No managerial role" (d) "Management was not necessary". We created a binary variable (*having a manager*) coded 1 if there is management ("yes" to a, b, or c) [whether or not the respondent was a manager] and 0 if management was not necessary.

[2] A detailed non-response bias analysis shows that respondents and non-respondents are similar on most observable indicators, including citation counts, being in the top 1%, number of authors, publication year and inter-institutional collaboration. The only major difference between respondents and non-respondents is that clinical medicine researchers are less likely to respond, although even clinical medicine has a response rate over 20%. We also find somewhat lower response rates among papers with many authors (over 6), although even for papers with over 20 authors, the response rate is over 20%.

[3] The survey had 188 questions in total, although because of skip logics and variations in team size, most respondents were asked fewer items.

4.1.4. Decentralization

Decentralization captures the extent to which lower level employees have the discretion to make independent decisions (Hage and Aiken, 1967). Here, we measure decentralization in the scientific work team with a binary variable based on the question:

> *Decentralization*: "During the course of the project, graduate students developed on their own changes in the research protocol".

4.2. Explanatory variables

4.2.1. Size

Our key predictor is size of the project team (Blau, 1970). To measure the size of the project team, we count all authors, collected from Web of Science, and the non-author project members (e.g., collaborating researchers (including post-docs), graduate students, undergraduate students, and technicians), collected from our survey, and sum these to calculate the total number of members in the project. Thus, our size measure is not limited to authors on the paper. In our sample, the minimum is 2 and maximum is over 500. Because we expect this effect is better captured by the order of magnitude (Blau, 1970), following Blau and others, we use the log of the number of members as our key size measure. Note that we are measuring the size of the project team producing this focal paper, not the size of the lab in which the team members work. The size of the lab is also an interesting area for research (see Carayol and Matt, 2004; Mairesse and Turner, 2005). However, some labs are organized as largely independent projects sharing space and equipment and under a common director, while others may be more interdependent, jointly producing shared papers (cf. Brown and Ross, 2013; Rifkind and Rifkind, 2009). Furthermore, a project may contain researchers from multiple labs collaborating (which would be missed if the lab was the unit). In this study, we are focusing on the individual paper, and hence the size of the project that produced the paper (rather than the lab) is the measure we are using. For an analysis of the division of labor at the level of the lab, see Shibayama et al. (2015).

In addition, we do robustness tests excluding the top 1% largest groups, which have more than 30 people in their project, to see how sensitive these size–structure relationships are across an even modest size range. We also replicate the models using log number of authors as an alternative size measure.

4.2.2. Interdisciplinarity

Prior work also suggests diversity of the research group should affect bureaucratic structuring (Kralewski et al., 1985). We measure diversity as the number of research fields represented in the project team. The survey asked the fields of expertise associated with co-authors (up to 7) for the paper.[4] We provided the respondents with a list of 29 fields to select from (Lee et al., 2015). We count the different fields of expertise in the author list and use the count as a measure of interdisciplinarity. The minimum is 1 and maximum is 6.

4.2.3. Interdependence

Van de Ven et al. (1976:324) define task interdependence as: "the extent to which unit personnel are dependent upon one another to perform their individual jobs." (see also Mohr, 1971). We might think of interdependence from a production function perspective as the extent to which production depends on the joint activity of multiple members of the work unit (rather than the aggregation of individuals' product). Prior work suggests scientific fields vary in their mean levels of interdependence (Fuchs, 1992; Hargens, 1975; Shinn, 1982; Walsh and Maloney, 2007). Building on this prior work in organization theory and in the sociology of science, we classify fields into high and low interdependence fields to test the direct effect of interdependence on bureaucratization and also the contingency effect of task interdependence on the size–structure relationship. Since the Scientist Survey does not provide information about field interdependence, we start with data from an earlier survey–the Scientific Communication and Scientific Work survey (Walsh and Maloney, 2007). This survey, conducted in 1998, has a measure of interdependence, based on Mohr (1971).

The survey asks, on a 7 point scale from 1 – "very little" up to 7" – to a great extent", "To what extent do the people in your research group have one person jobs (i.e., in order to get the work out, to what extent do group members independently accomplish their own assigned task)?". The means for this question across 4 fields (biology, mathematics, physics, and sociology) show significant field differences ($p < .05$) and that physics has higher interdependency than biology, consistent with prior data about distinctions between physics and biology in terms of interdependence, routinization of work, collaboration, and credit systems (Biagioli, 2003; Brown and Ross, 2013; Hargens, 1975; Rifkind and Rifkind, 2009; Whitley, 1984). Using this distinction as a starting point, we then group fields into a physics-like group and a biology-like group, that is, high interdependency group and low interdependency group (Brown and Ross, 2013; Rifkind and Rifkind, 2009). For example, Hargens (1975) argues that chemistry has high interdependency (even at the project level) and is similar to physics because both have high paradigm development (see also Collins, 1975; Fuchs, 1992; Whitley, 1984). Similarly, Shinn (1982) argues that interdependence was high in chemistry (higher even than solid state physics). We classified physics, chemistry, and engineering into a group of high interdependence fields, and biology, medicine, and agricultural science into a group of low interdependence fields. For this analysis, we exclude social sciences and mathematics. While there is likely to be significant measurement error in this classification, especially when applied to project-level data, we are testing to see if, even in the face of measurement error, we see significant differences in bureaucratic structuring between high and low interdependence fields and differences in the effects of size contingent on being in a high or low interdependence field. Hence our measure provides a conservative test of this contingency effect.

4.3. Controls

We also expect organizational and field environment affect bureaucratization (Child, 1973; Collins, 1975; Fuchs, 1992; Whitley, 1984).

4.3.1. Technology of production

As noted above, based on prior work, we argue that field differences in part represent differences in the technology of production (including uncertainty, analyzability, and interdependence) that contingency theory argues should affect the underlying tendencies toward more or less bureaucratic structuring (cf. Child 1973). Thus, using 10 field categories, we created field dummies, where chemistry is the reference group, as a proxy for these production

[4] In our sample 84% of cases have 7 or fewer authors and so we have complete information on our continuous measure of interdisciplinarity. We also create a binary measure (multiple fields or not) for robustness. If we use the binary measure, then of those with over 7 authors, 63% are coded as a multi-field team, based on the answers to the 7 reported authors. Using this binary measure, only 6% of cases are possibly affected by missing information on the remaining authors (with some of those possibly miscoded as not multi-field when they are in fact). Our findings are robust to excluding these cases with potential measurement error.

technology differences (Collins, 1975; Fuchs, 1992; Hargens, 1975; Shinn, 1982; Whitley, 1984).

4.3.2. Organizational context

University R&D. We measure organization size using the log of total R&D expenditures of the respondent's university, from the 2007 AUTM U.S. licensing activity survey.

Public vs. Private university. We classified universities into public or private and created a binary variable that is 1 if the university is public.

5. Results

We begin with a discussion of descriptive statistics (see Table 1). Average project size is 7 members (including an average of almost three non-authors). The mean of interdisciplinarity is 2 fields. About three-quarters of projects have internal division of labor, while 24% and 31% report some external division of labor and existence of a non-author technician, respectively (cf. Leahey and Reikowsky, 2008). Thus, division of labor, including use of technicians, is quite common in contemporary science (Barley and Bechky, 1994). The percentage of projects employing standardization ranges from 46% to 66% across the two measures. Sixty-one percent have hierarchical reporting and 96% of scientific projects have some form of management. Furthermore, 55% of projects have a decentralized structure. Table 1 also gives the bivariate correlations among the variables. Consistent with prior work from other kinds of organizations (Blau, 1970; Child, 1973), we find that in scientific project groups, the log of the size variable is more strongly and highly correlated with the structure variables than the size variable of count of total members (results available from author), which shows the existence of curvilinearity in the relationship (Blau, 1970). For the variables of bureaucratic structuring, correlations between components in different dimensions range from .05 to .43 and most of them are less than .25. This shows that while each of these dimensions is correlated, they are also distinct.

To further examine the composition of project teams, we break down the project members into authors and non-authors (including other PhD-level researchers, technicians, and students). We report the results overall and by field (Table 2). The mean project group size is high in agricultural sciences, environmental/geoscience, and medicine. The rate of non-authors out of total group members is also high in agricultural sciences. About a half of members are non-authors in computer science/math and social science. However, in biology and chemistry, most members (more than 70%) are included as authors. This shows that measuring group size only with authors may misrepresent the true size of the project group (Horta and Lacy, 2011; Shapin, 1995). Moreover, since division of labor occurs among scientists at various career stages as well as among peers (Bonaccorsi and Daraio, 2005), defining group size including both authors and non-authors, including post-docs, technicians and students, is more reflective of true project size.

5.1. Size, interdisciplinarity, and bureaucratization of science

We begin with our test of the effects of size (H1) and interdisciplinarity (H2) on bureaucratic structuring in science. We estimate probit regression models regressing our measures of division of labor, standardization, hierarchy and decentralization against the log of project group size and interdisciplinarity. We also control for university R&D budget size (measuring organizational size) and public status, as well as field (to control for uncertainty, depen-

Table 1
Descriptive statistics and correlation matrix.

	Variable			N	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Dependent variables	Division of labor	1	Internal DoL	1188	0.77	0.42	0	1	1.00														
		2	External DoL	1177	0.24	0.42	0	1	**0.13**	1.00													
		3	Specialist role (anytech)	1223	0.31	0.46	0	1	**0.11**	**0.18**	1.00												
	Standardization/ formalization	4	Regular check	1132	0.46	0.50	0	1	**0.12**	**0.12**	**0.11**	1.00											
		5	Regular meeting	1179	0.66	0.47	0	1	**0.20**	0.05	**0.09**	**0.40**	1.00										
	Hierarchy	6	Hierarchical reporting	1148	0.61	0.49	0	1	**0.22**	**0.17**	**0.13**	**0.39**	**0.20**	1.00									
		7	Having a manager	1192	0.96	0.21	0	1	**0.17**	**0.09**	**0.08**	**0.16**	**0.13**	**0.19**	1.00								
	Decentralization	8	Decentralization	1167	0.55	0.50	0	1	**0.15**	**0.12**	0.05	**0.43**	**0.24**	**0.23**	**0.14**	1.00							
Explanatory variables	Size	9	Project group size (log)	1223	1.66	0.63	0.69	6.40	**0.16**	**0.34**	**0.25**	**0.14**	**0.07**	**0.16**	**0.14**	**0.09**	1.00						
		10	# of all collaborators	1223	7.03	17.86	2	601	0.05	0.14	**0.12**	0.01	0.04	0.01	0.03	0.04	**0.48**	1.00					
		11	# of authors	1223	4.28	3.29	1	205	**0.15**	**0.22**	**0.14**	**0.09**	0.02	**0.09**	**0.08**	0.02	**0.56**	0.18	1.00				
		12	# of non-authors	1223	2.75	17.59	0	600	0.02	**0.10**	**0.08**	−0.01	0.04	−0.01	0.02	0.04	**0.38**	**0.98**	−0.01	1.00			
	Interdisciplinarity	13	Interdisciplinarity	1220	1.65	0.86	1	6	**0.20**	**0.20**	**0.13**	**0.12**	**0.07**	**0.12**	**0.11**	−0.01	**0.31**	0.04	**0.30**	−0.02	1.00		
	Field interdependence	14	High interdependence	904	0.31	0.46	0	1	**−0.17**	−0.07	**−0.18**	**0.12**	0.05	−0.04	**−0.21**	**0.12**	**−0.18**	−0.04	**−0.14**	−0.02	**−0.22**	1.00	
Controls	Organizational context	15	University R&D size	926	19.88	1.09	16.03	22.11	0.01	0.02	0.00	−0.05	0.03	**−0.15**	**0.06**	−0.02	−0.02	0.05	0.02	0.05	0.00	−0.04	1.00
		16	Public university	1005	0.68	0.47	0	1	−0.02	−0.02	−0.09	0.02	−0.03	−0.06	−0.01	**0.11**	−0.03	0.02	−0.04	0.03	−0.05	**0.13**	**0.11**

Notes: Project group size = log of # of collaborators in a project group. Bold numbers in correlation matrix significant at .05 level. For correlations between anytech and size variables, our size variables exclude technicians.

Table 2
Project group composition, by field.

Field	N	Collaborators			Non-authors			
		Total (group size) Mean	Authors Mean	Non-authors Mean	Post-docs Mean	Grads Mean	Undergrad Mean	Technician Mean
Ag science	84	11.52	3.46	8.06	1.70	3.45	0.44	2.48
Biology	271	6.30	4.83	1.47	0.47	0.32	0.14	0.54
CS/math	69	5.29	2.63	2.66	0.66	1.55	0.38	0.08
Chemistry	101	5.29	3.79	1.49	0.46	0.38	0.45	0.20
Engineering	75	5.27	2.73	2.54	0.72	0.99	0.49	0.34
Env/geo	103	7.95	4.12	3.83	1.23	0.81	0.88	0.92
Materials	33	6.57	3.94	2.64	0.60	0.73	0.90	0.40
Medicine	238	7.46	5.06	2.40	0.90	0.37	0.17	0.96
Phys/space	135	6.62	4.24	2.39	1.33	0.41	0.16	0.49
Social science	114	5.51	2.75	2.76	1.47	0.76	0.32	0.21
All	1223	7.03	4.28	2.75	0.89	0.77	0.31	0.78
Field difference		***	***	***	*	***	***	***

*$p<.10$; **$p<.05$; ***$p<.01$.

Table 3
Dependent variables: measures of bureaucratic structuring, probit regressions on size and interdisciplinarity.

	Division of labor			Standardization		Hierarchy		Decentralization
	Internal DoL	External DoL	Anytech	Regular check	Regular meeting	Hier. report	Manager	Decentralization
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Project group size	0.23**	0.68***	0.45***	0.25***	0.11	0.27***	0.39**	0.27***
	(0.10)	(0.11)	(0.10)	(0.09)	(0.09)	(0.10)	(0.19)	(0.10)
Interdisciplinarity	0.38***	0.19**	0.00	0.15**	0.10	0.09	0.17	−0.02
	(0.09)	(0.08)	(0.07)	(0.07)	(0.07)	(0.08)	(0.14)	(0.07)
University R&D	0.02	0.03	0.01	−0.07	0.04	−0.18***	0.17**	−0.04
	(0.06)	(0.06)	(0.05)	(0.05)	(0.05)	(0.06)	(0.08)	(0.06)
Public (v. private)	−0.02	−0.07	−0.19	0.07	−0.07	−0.06	0.17	0.16
	(0.14)	(0.15)	(0.13)	(0.13)	(0.13)	(0.13)	(0.22)	(0.13)
Tech of production								
Ag science	0.10	−0.58*	1.03***	−0.93***	−0.58**	−0.26	–	−0.57*
	(0.31)	(0.33)	(0.32)	(0.30)	(0.28)	(0.30)		(0.30)
Biology	0.25	−0.23	0.84***	−0.43*	−0.13	−0.06	–	−0.42*
	(0.24)	(0.24)	(0.28)	(0.23)	(0.23)	(0.23)		(0.24)
CS/math	−0.44	−0.93***	−0.48	−0.94***	−0.34	−0.69**	−1.74***	−0.70**
	(0.29)	(0.35)	(0.41)	(0.29)	(0.29)	(0.29)	(0.41)	(0.29)
Engineering	−0.28	−0.24	0.51	0.15	0.55	−0.09	-0.64	0.07
	(0.30)	(0.33)	(0.34)	(0.31)	(0.33)	(0.30)	(0.54)	(0.32)
Env/geo	−0.05	−0.13	0.91***	−0.82***	−0.04	−0.28	-1.28***	-0.04
	(0.30)	(0.30)	(0.31)	(0.28)	(0.28)	(0.28)	(0.44)	(0.30)
Materials	−0.18	0.25	0.26	−0.10	0.26	−0.32	–	0.65
	(0.40)	(0.40)	(0.44)	(0.40)	(0.43)	(0.37)		(0.50)
Medicine	0.00	-0.41	0.82***	−0.70***	−0.25	−0.24	-0.28	-1.08***
	(0.24)	(0.26)	(0.28)	(0.24)	(0.23)	(0.24)	(0.49)	(0.25)
Phys/space	−0.23	−0.99***	0.37	−0.36	−0.08	−0.41	−1.40***	−0.62**
	(0.27)	(0.31)	(0.31)	(0.27)	(0.26)	(0.27)	(0.40)	(0.27)
Social science	0.52*	−0.16	−0.08	−0.94***	−0.17	−0.26	−1.13***	−0.94***
	(0.30)	(0.30)	(0.34)	(0.28)	(0.26)	(0.27)	(0.43)	(0.28)
Obs	899	890	921	854	888	872	897	880
F	F(13,899)	F(13,890)	F(13,921)	F(13,854)	F(13,888)	F(13,872)	F(10,900)	F(13,880)
	3.63***	5.96***	5.58***	3.73***	1.43	2.53***	3.66***	4.55***
Adj. Wald test of tech	F(9,903)	F(9,894)	F(9,925)	F(9,858)	F(9,892)	F(9,876)	F(6,904)	F(9,884)
of production	1.82*	2.47***	4.49***	3.78***	1.64	1.09	4.87***	5.56***

Notes: When we regress anytech on size and other controls, our size variable excludes technicians. The reference group of tech of production is chemistry. For column 7, cases from excluded field dummies are included in the reference group. *$p<.10$; **$p<.05$; ***$p<.01$.

dence and production technology). Table 3 shows the results.[5] We can see that, across almost all measures of bureaucratic structuring, group size has a significant positive impact (except *regular meeting,* column 5, where the effect is positive but not significant), supporting our Hypothesis 1. For example, for the average chemistry project team in a private university, increasing the project size from 3 to 7 members (from the 25th to the 75th percentile) raises the probability of internal division of labor 7%; the probability of standardization (*regular check*) 13%; the probability of hierarchy (*hier. report*) 12%; and the probability of decentralization 11%.

Interdisciplinarity shows a positive significant effect on division of labor, but not on hierarchy, partially supporting Hypothesis 2. For example, for the average chemistry project team in a private university with 5 members (median size), increasing interdisciplinarity from 1 to 2 fields (from the 25th to the 75th percentile) raises the

5 As we described in the data section, we limited responses to projects with at least two members (i.e., the subpopulation) because bureaucratic structuring has meaning when there are at least two people. However, we estimate SEs in all regression models displayed in this paper considering the unconditional, full population to avoid biased results, because subpopulation sizes within strata are random and the true subpopulation size is not known, and needs to be estimated on the full population (West et al., 2008).

probability of internal division of labor 16% and that of external division of labor 25%.

5.2. Bureaucratization, interdependence and the size-interdependence contingency

Our Hypothesis 3 predicts the relationship between field interdependence and different dimensions of bureaucratic structuring. Table 4 shows the direct effect of field interdependence on each dimension of bureaucratic structuring (controlling for project size, interdisciplinarity, university size and public vs. private). First, field interdependence has a negative relation with all components of division of labor although it is not significant for *external DoL* (columns 1, 3, and 5) whereas, it has a positive significant relation with standardization (columns 7 and 9), consistent with Hypotheses 3a and b. Second, although field interdependence is associated with less hierarchy, its effect on hierarchy as use of vertical communication channels is not significant (column 11), only qualitatively supporting Hypothesis 3c. Third, column 15 shows that field interdependence has a significant positive relation with decentralization (discretion), which does not support Hypothesis 3d. One possible explanation for this result is that, if standardization is positively related to interdependence (which we find), even highly interdependent team members can have substantial discretion, much the way that standardization and modularization of components in a computer allows for innovation in, for example, disk drives or monitors. Overall, the results generally support Hypothesis 3 with a few weak effects and with the exception of decentralization (discretion). Notably, the effects of interdependence on each indicator of a particular component of bureaucratic structuring show the same patterns, but the effects are distinct from indicators for other dimensions, which validates the within-group similarities and inter-group differences of indicators. It is also noteworthy that the effects of size and of interdependence are not the same across different components of bureaucratic structuring, further suggesting some independence across these components (since they have different drivers).

Hypothesis 4 argues that the linkages between size and structure are generally stronger when interdependence is higher (Fuchs, 1992). Table 4 also shows the contingency effect of size on bureaucratic structuring across a change in field interdependence. First, the coefficients for size are all positive (except for *having a manager*), showing that size drives more bureaucratic structuring even controlling for interdependence-related variables. Second, the interaction term on size and interdependence shows a positive direction on bureaucratic structuring (except *regular check*), but the coefficient is only significant for *internal DoL* and *anytech* in division of labor, and *having a manager* in hierarchy (see columns 2, 6, and 14). However, since we cannot directly interpret the interaction effects reading the coefficients on the interaction term in a non-linear model, we further examine the interaction effects on *internal DoL*, *anytech* and *having a manger* using a simulation-based approach (Zelner, 2009). This enables us to test the significance of the difference in predicted probabilities when the contingency variable (i.e., field interdependence) changes at different size values.[6]

[6] We set the values of all other variables at zero in the simulation following Zelner (2009). Since *estsimp* command in the simulation does not support *svy* estimation, for the simulation, we estimate parameters using *pweight* to include different sampling weights, limiting to cases with at least two members, but not adjusting SEs by strata. However, including and excluding variation adjustment by strata do not generate any substantial differences in the results. For example, the SE of the interaction term in column 2, Table 4, which is adjusted by sampling weights and strata is .253. The SE of the interaction term in the simulation ignoring strata is .252. This suggests that the stratification adjustment has only minor effects on the estimation and ignoring strata for the simulation is acceptable.

Table 4
Dependent variables: measures of bureaucratic structuring, probit regressions on size, interdependence and size-interdependence interaction.

	Division of labor						Standardization				Hierarchy				Decentralization	
	Internal DoL		External DoL		Anytech		Regular check		Regular meet		Hier.report		Having a manager		Decentralization	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Size	0.21*	0.06	0.62***	0.59***	0.42***	0.25*	0.20*	0.27**	0.09	0.04	0.24**	0.16	0.20	−0.20***	0.21**	0.13
	(0.11)	(0.13)	(0.13)	(0.15)	(0.12)	(0.13)	(0.11)	(0.13)	(0.10)	(0.12)	(0.11)	(0.13)	(0.24)	(0.06)	(0.11)	(0.12)
Interdisc	0.40***	0.40***	0.19**	0.19**	0.00	0.01	0.17**	0.17**	0.10	0.10	0.08	0.08	0.08	0.09	0.00	0.01
	(0.10)	(0.10)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.16)	(0.15)	(0.08)	(0.08)
Univ R&D	0.02	0.02	0.03	0.03	0.01	0.01	−0.05	−0.05	0.06	0.06	−0.17***	−0.16***	0.09	0.09	−0.02	−0.02
	(0.07)	(0.07)	(0.07)	(0.07)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.09)	(0.08)	(0.06)	(0.06)
Public univ	−0.04	−0.04	0.00	0.00	−0.17	−0.17	0.04	0.04	−0.21	−0.21	−0.07	−0.06	0.23	0.22	0.23*	0.23*
	(0.16)	(0.16)	(0.16)	(0.15)	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)	(0.14)	(0.29)	(0.29)	(0.13)	(0.14)
High interdep	−0.27*	−0.97**	−0.01	−0.24	−0.56***	−1.80***	0.54***	0.93**	0.37**	0.07	−0.02	−0.44	−1.08***	−1.98***	0.51***	0.04
	(0.15)	(0.40)	(0.16)	(0.45)	(0.15)	(0.42)	(0.14)	(0.38)	(0.14)	(0.38)	(0.14)	(0.39)	(0.30)	(0.53)	(0.14)	(0.39)
Interdep*Size		0.47*		0.13		0.76***		−0.25		0.20		0.27		0.54*		0.31
		(0.25)		(0.25)		(0.24)		(0.22)		(0.23)		(0.24)		(0.30)		(0.24)
Obs	676	676	669	669	685	685	646	646	671	671	655	655	664	664	664	664
F	F(5, 666) 5.45***	F(6, 665) 5.69***	F(5, 659) 7.92***	F(6, 658) 6.90***	F(5, 675) 7.42***	F(6, 674) 7.73***	F(5, 636) 4.16***	F(6, 635) 3.68***	F(5, 661) 2.00*	F(6, 660) 1.77	F(5, 645) 2.99**	F(6, 644) 2.65**	F(5, 654) 5.48***	F(6, 653) 7.85***	F(5, 654) 3.87***	F(6, 653) 3.16***

* $p < .10$; ** $p < .05$; *** $p < .01$.

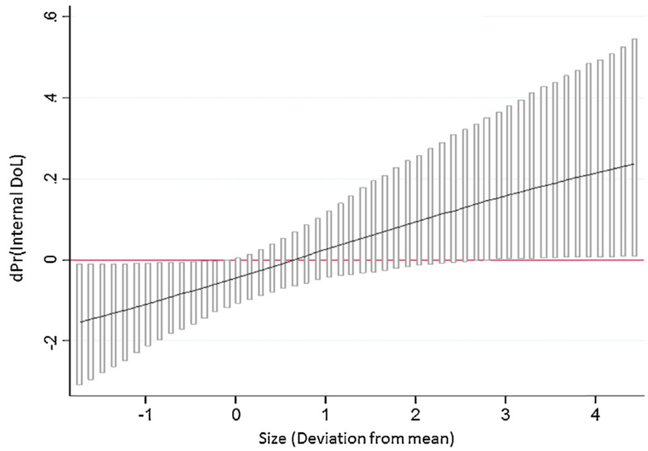

Fig. 1. The difference in predicted probabilities of internal division of labor associated with a change from low to high interdependence at different levels of size.

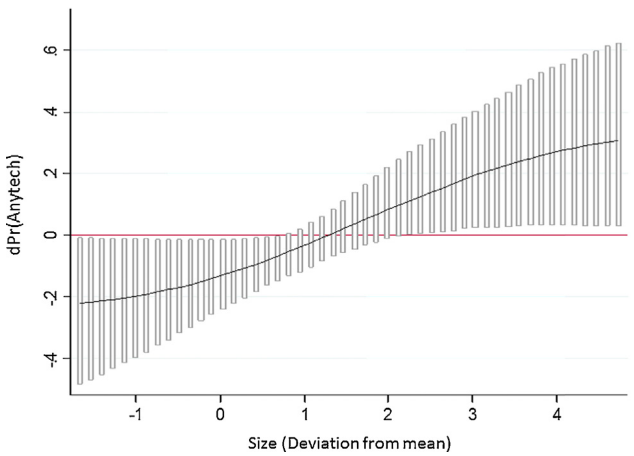

Fig. 2. The difference in predicted probabilities of having any technician associated with a change from low to high interdependence at different levels of size.

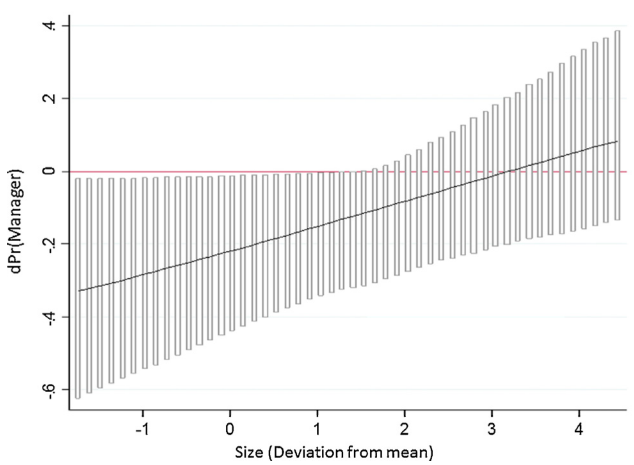

Fig. 3. The difference in predicted probabilities of having a manager associated with a change from low to high interdependence at different levels of size.

We show the results of the simulations in Figs. 1–3 . Fig. 1 depicts the differences in predicted probabilities of *internal DoL* associated with an increase in interdependence at different levels of size (in standard deviation units) along with the 90 percent confidence interval for this difference. We can see the difference in predicted probabilities is increasing, but is only significant below −.5 SD and above 3.5 SD from the mean size (i.e., less than 4 members or more than 45 members in unlogged values), which is the region where the 90 percent confidence interval does not include zero. The difference in predicted probabilities of *anytech* between high and low interdependence in Fig. 2 is significant up to just above the mean (i.e., 5 members except technicians) and above 2.5 SD (i.e., more than 22 members except technicians). However, in Fig. 3, we can see significant differences in predicted probabilities of *having a manager* only in the smaller groups, less than 7 members. Since, in our sample, 96% has a manger (and this percentage is positively associated with size) the effect of size on having a manger would be clearer in the lower level of size values. Thus, we can see some evidence to support the larger effect of project size on bureaucratic structuring in high interdependence than low interdependence fields, consistent with Hypothesis 4. A large, interdependent group may be more likely to divide up the tasks and also require a person specializing in the coordination function in order to take advantage of productivity gains and reduce uncertainty over which members are responsible for which aspects of the interdependent task set (Lawrence and Lorsch, 1967; Van de Ven et al., 1976).

5.3. Robustness tests

5.3.1. Endogeneity

While prior work suggests that size drives structure, rather than structure affecting size (Baron et al., 1999a; Dewar and Hage, 1978; Meyer, 1972), we might still have concerns in our data regarding simultaneous determination between size and structure. For example, perhaps a higher productivity in bureaucratically structured projects can account for the relation between bureaucratization and size (such that projects that are more bureaucratic produce more, and hence are more successful at receiving grants or other funding, which both allows and mandates growth, see Salonius, 2008). Thus, there may be reasons to believe the bureaucracy–size relation is an iterative process.

If size is a function of structure, size will be correlated with the error term and our estimates will be biased and inconsistent. Therefore, we check for endogeneity in the size variable in our baseline models given in Table 3. To test for endogeneity of the size variable, we use a control function approach (Colombo and Grilli, 2005; Wooldridge, 2010). The number of citations per faculty in the department of the respondent's university in 1993 (National Research Council, 1995) is used as an exogenous variable that predicts size of project teams, but does not have a direct observed effect on the structure of a project in 2001–2006. We match our respondents' field and institutional affiliation to the National Research Council's field and affiliation records and collect data on citations per faculty member from the NRC graduate school rankings report (National Research Council, 1995). The number of citations per faculty shows how research active or how capable of high impact research the respondent's co-workers are, which can give her access to a bigger pool of potential collaborators. Therefore, people who are in departments with a larger number of research-active colleagues are likely to have larger research projects. However, that environment is unlikely to directly affect the structure of each project in 2001–2006 cohorts of publications. We argue that this is a proper exogenous variable for this test, assuming no correlation with any error terms in the equations, because the characteristics of university departments do not change dramatically over time and these unobtrusive data are clearly prior to our survey data (and so are not caused by current project structure). First, we run the OLS regression of size on log of the 1993 citations per faculty in our respondent's department and all other variables, and save the residuals $\hat{v}$. The 1993 citation number per faculty has a significant positive effect on size ($p < .05$, consistent with our assumptions).

Second, we run the probit of each of our dependent variables on size, all other controls, and $\hat{v}$. We test the null hypothesis that size is exogenous based on the significance of the coefficient on $\hat{v}$, because $\hat{v}$ controls for the endogeneity of size in the equation (Wooldridge, 2010). Based on our test, we find the coefficient on $\hat{v}$ is not significant in any models ($p > .10$) and thereby cannot reject that size is exogenous, except in the models of *internal DoL* ($p < .05$) and *regular meeting* ($p < .10$). However, the coefficient of size on *regular meeting* is still significant and positive even after controlling for the endogeneity of size with $\hat{v}$. Therefore, although we cannot completely rule out endogeneity, especially, in column 1 (*internal DoL*) in Table 3, we do not find evidence of endogeneity in our size measure in most models. This result is also consistent with prior research that size is an exogenous predictor of structure (Baron et al., 1999a; Meyer, 1972).

5.3.2. Ordinal measures of bureaucratization

We also measured structure using ordered variables. While we framed the research question as whether or not such bureaucratic structures have been implemented in the project, it is also of interest to see if intensity of use increases with size. Indicators of bureaucratic structuring (except *anytech* in division of labor and *having a manager* in hierarchy) were originally measured on five-point scales: from "not at all" to "very much". As a robustness check, we ran ordered probit models using these ordinal measures (Table 5). Results are consistent with our baseline model (Table 3). In particular, we find that size (log of the number of collaborators) has a positive, significant effect on all of our ordinal measures of bureaucratic structuring, except for *internal DoL* and *regular meeting*. However, because the parallel-lines assumption of ordered probit models is often violated in the ordered response model, we also run the generalized probit model, relaxing this assumption (Williams, 2007). The generalized probit model is equivalent to a series of binary probit regression with categories of the dependent variable combined in succession. The results in Table 5 show the probit regression with category 1 vs. categories 2–5 (1_Size); categories 1 and 2 vs. categories 3–5 (2_Size); and so on, relaxing the parallel-lines assumption only for dependent variables that violate the assumption. Our size variable does not violate the parallel-lines assumption in columns 2 and 5, so the same coefficient on size is given across all probit regressions. For other models, we can see that the effect is significantly positive in the probit regression with category 1 vs. categories 2–5. The effect becomes weaker as the cut moves up. This robustness check shows that the effect of size is clearer on the existence vs. non-existence of bureaucratized structures than predicting the different levels of bureaucratization.

5.3.3. Other robustness checks

We ran additional tests to check the robustness of our results to alternative measures of size, as well as within-field variation in size.[7]

As an additional measure of size, we test the log number of authors, which is a commonly used measure of research group size, collected from Web of Science (which has the advantage of being collected separately from the survey). Using log number of authors, we again find significant positive effects on all measures of bureaucratic structuring except *anytech* and *regular meeting*, where we see positive but insignificant effects. We additionally test the effect of size of non-authors on bureaucratic structuring and find consistently significant positive effects in all models except *internal DoL* and *having a manager*, where we see positive but insignificant effects. We considered whether some aspects of bureaucratic structuring were more sensitive to either author count or non-author project members. However, based on tests of each independently and together (results available from author), we do not see any clear difference between the effects of author size and those of non-author size on bureaucratic structuring, although this may be an interesting area for future research. Our main interest in the size measure is to measure true size of project groups including both authors and non-authors, and the results by using this measure are consistent with those by a commonly used size measure, i.e., number of authors.

Moreover, to see how sensitive results are to outliers, we test the baseline models in Table 3 excluding the top 1% largest groups from our sample (those with over 30 members) and find consistent results between models with the full sample and the size-truncated sample. In addition, to see if our results are sensitive to the level of aggregation of fields, we rerun the regressions in Table 3 using 20 fields instead of 10 (see Appendix A), with the two social science fields collapsed into one and the multidisciplinary field distributed to the other 20 based on the references in the paper. The results are robust to this finer level control for technology of production. We again find that size is still significant in all models except *regular meeting* and that field effects are significant for all of the models except *hierarchical reporting*, including the effect on *regular meeting* now being significant (results available from author).

Finally, we check the effect of size on structure within each field and examined variation across fields in impact of size (Collins, 1975; Fuchs, 1992). Even within field, the effects of size are generally positive, although with small sample sizes in each field, often not significant. For example, for *internal DOL*, 8 of 10 fields show a positive relation between size and internal division of labor and one field (Physics) is significant. For *external DOL*, 10 of 10 are positive, and eight of those are significant. Across all the measures, the effects of size are positive in the majority of fields, though not always significant. We also find variation across fields on impact of size along the different indicators of bureaucracy, suggesting there may be important size by field contingency effects (Child, 1973; Fuchs, 1992), consistent with our results above on field-level interdependence.

6. Implications

Our results suggest that the increasingly common large research groups in science have more bureaucratized work organization. In the following sections, we discuss the potential implications of these changes for scientific training, careers, and authorship.

6.1. Training and careers

As scientific projects become increasingly bureaucratized, will we see a concomitant transformation in the training and career progression of scientists? Traditionally, scientific training and careers followed a craft model (Alberts et al., 2014; Collins, 1975; Delamont and Atkinson, 2001; Hackett, 1990; Hagstrom, 1964; Hargens, 1975; More, 1980). As graduate students, aspiring scientists apprenticed themselves to master scientists, where they spent years learning the trade, gradually building up to the task bundle of independent researchers (Beechy, 1982; Delamont and Atkinson, 2001; Hagstrom, 1964; Walsh, 1989). One important role of the master in this craft training is to make sure that the apprentice is exposed to the various tasks in the bundle, so that the young craftsman can fully execute the skills of her trade (Hagstrom, 1964; More, 1980). This training culminates in a dissertation project for which the apprentice scientist takes primary responsibility (often appearing as first author on the related papers). From this point,

[7] The results for robustness tests are available from authors on request.

Table 5
Dependent variables: measures of bureaucratic structuring, ordered probit and generalized ordered probit regressions on size.

	Division of labor		Standardization		Hierarchy	Decentralization
	Internal DoL	External DoL	Regular check	Regular meeting	Hier. report	Decentralization
	(1)	(2)	(3)	(4)	(5)	(6)
Ordered probit						
Size	0.11	0.63***	0.14*	0.01	0.19**	0.17**
	(0.07)	(0.10)	(0.08)	(0.08)	(0.08)	(0.08)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Generalized ordered probit						
1_Size	0.30***	0.60***	0.25***	0.16	0.20**	0.28***
	(0.10)	(0.09)	(0.09)	(0.10)	(0.08)	(0.09)
2_Size	0.22**	0.60***	0.14	-0.10	0.20**	0.11
	(0.09)	(0.09)	(0.10)	(0.10)	(0.08)	(0.09)
3_Size	0.05	0.60***	−0.02	−0.10	0.20**	0.07
	(0.09)	(0.09)	(0.12)	(0.10)	(0.08)	(0.10)
4_Size	−0.18	0.60***	−0.18	−0.04	0.20**	0.14
	(0.13)	(0.09)	(0.13)	(0.12)	(0.08)	(0.10)
Controls	Yes	Yes	Yes	Yes	Yes	Yes

* $p < .10$; ** $p < .05$; *** $p < .01$.

the journeyman scientist will generally spend several years moving through one or more post-doctoral positions, where she can provide competent journeyman work, and also hone her skills, with the goal of eventually becoming a master at the head of one's own lab (More, 1980; Sewell, 1986).

However, the growth of team science, and the dearth of lab head positions (Alberts et al., 2014; National Research Council, 1998; Pavlidis et al., 2014), may be producing an industrialization of the scientists' careers (Hargens, 1975), similar in nature to the transformation of craft work into semi-skilled participants in a division of labor controlled by a manager (Bendix, 1956). Hackett (1990) argues the "professor-employer's" dependence on the research assistant's productivity for maintaining the flow of funding may lead to premature specialization, limiting the apprentice's exposure to the breadth of tasks in the bundle of a fully trained, for example, geneticist or organic chemist, analogous to the decline in apprenticeship training in other crafts (Hargens, 1975; More, 1980). At the same time, technicians are also often key participants in the increasingly complex division of labor in a lab (Barley and Bechky, 1994). Similarly, Hagstrom (1964) argues that there may be a tradeoff between the training function of the professor–student relationship and the efficiency/productivity of the research team. There has been substantial, long-running discussion in the case of biomedical researchers on the social problem of the permanent post-doc (Alberts et al., 2014; National Research Council, 1998). Increasingly, the large-scaled bureaucratized structure may create positions of what might be called "sub-scientist" (in contrast to the fully-integrated scientist of the craft model), whose career, and perhaps even training, will focus on participating in science in a permanent supporting role, rather than as a temporary state on the way to becoming an autonomous lab head (Hagstrom, 1964; Hargens, 1975). Even as far back as the early 20th century, Weber noted the relatively higher level of bureaucratization of academic careers in the US, compared to Germany in his day (Weber, 1946). In the 1960s, with the rise of Big Science, Hagstrom (1964) notes the beginnings of what he refers to as "professional technicians", with specialist skills but who are not as committed to the research question nor rewarded by the scientific recognition system.[8] Hackett (1990) reports that these "academic marginals" positions in universities have grown at a faster rate than professor positions. Salonius (2008) documents this transformation in the case of Canadian biomedical researchers and discusses the implications of this transformation for the training of scientists. Shibayama et al. (2015) document the extent of specialization in the roles of entrepreneur (tasked with generating funding and selecting projects, rather than executing the research) among Japanese biomedical researchers. More (1980) argues that one aspect of industrialization of craft occupations is separation of the master from the everyday shop work, with training done by journeymen, or apprentices left to learn what they can while spending most of their time specializing in a specific task in the shop. We may be seeing such a transformation in academic craftsmanship. And, the process can be self-reinforcing, with organizations simultaneously generating and demanding sub-scientists (meaning those performing subordinate, dependent roles) and technicians for staffing large bureaucratically-structured projects (Stinchcombe, 1986). The continued growth of project size and increasing emphasis on productivity may be producing a fundamental transformation in scientific work. Thus, we may see a deskilling of scientific work (Braverman, 1974), as it becomes increasingly organized on bureaucratic principles based on division of labor, standardization (often codified in equipment) and hierarchy.

6.2. *Authorship*

There is also a mismatch between team science and individual credit allocation (Biagioli, 2003). For example, the average number of non-author project members (other researchers, technicians, and students) in our sample is just under 3 (out of 7 total), meaning that almost half of the research group is non-authors. Biagioli (2003) notes the struggles of different fields to deal with this credit problem in team science and how the solution varies by field. The recent debate about if, and how, to credit the thousands of researchers at CERN who confirmed the existence of the Higgs boson is one example (in the end, only two theorists got the Nobel prize) (Overbye, 2013). While this problem is not unique to science (this is a common feature of many work settings), what is unique is both the characteristics of the priority-based reputation reward system in science (Merton, 1957) and the recent transformation of the production process that is putting strains on that system.

In addition, as the roles of scientific workers become increasingly differentiated, the model of authorship lists representing a collaboration among peers becomes increasingly untenable (Biagioli, 2003). There is a growing need to differentiate the contributions of different members of the research team. Many of the members of the group, even on the author list, are located in posi-

[8] Hagstrom (1964) also notes that these professional technician roles, while implying division of labor, do not imply hierarchy: "At the same time the technician, like any professional, is not easily supervised, since he possesses an expertise his scientific supervisors lack." (pp. 254–255).

tions that may be outside the craft model. We suggest there may be a need for a reward system that more closely reflects the complexity of the division of labor in scientific groups and that provides specialist recognition and career paths for those who excel in sub-scientist roles. The movie industry, with extended detailed credits at the end of movies and large numbers of specialist Academy Awards, may be a good model for a team activity that depends on a variety of specialist semi-professionals and technicians (Becker, 1982; Pavlidis et al., 2014). Recent attempts to include a detailed footnote describing the division of labor on a paper may provide a step in this direction (Biagioli, 2003).

7. Conclusions

Scientific work is increasingly "organized". This provides an opportunity for incorporating organization theory into the study of science (cf. Chompalov et al., 2001; Collins, 1975; Fuchs, 1992). We find that university research groups commonly share the features of bureaucratic structuring, including division of labor, standardization and formalization, hierarchy, and decentralization. In addition, size is a key driver of this bureaucratic structuring, consistent with predictions based on economic theory (Becker and Murphy, 1992) and observations of private and public work organizations (Blau, 1970; Child, 1973). This paper extends those findings to show that academic science is also responsive to these rationalization pressures (Becker and Murphy, 1992; Weber, 1978). However, this bureaucratic structuring also highlights the tensions between the research production and teaching functions that academic labs provide (Hackett, 1990; Hagstrom, 1964; Pavlidis et al., 2014).

In addition, the findings suggest that the scope of the project (interdisciplinarity) increases the division of labor (Kralewski et al., 1985). There is growing interest in the study of interdisciplinarity (Hoffmann et al., 2013) and interdisciplinary teams (Fiore, 2008). This result suggests that interdisciplinarity might not lead to integrated research projects, but rather can lead to combinations of more or less independent bundles of tasks in each specialty (Chompalov et al., 2001). Future work is needed to understand the nature of integration in interdisciplinary research.

Field-level characteristics, related to the technology of production, also affect bureaucratization. We find, for example, that interdependence has significant effects on bureaucratic structuring, distinct from the effects of size, including negative effects on division of labor, but positive effects on standardization. Looking further, the effect of size on bureaucratization, especially division of labor, is larger in high interdependency than in low interdependency work settings (cf. Fuchs, 1992). We also find that controlling for field-level dummy variables shows significant differences in most measures of bureaucratic structuring. Therefore, there are significant cross-field differences in bureaucratization, and often in the strength of the size–structure relationship, suggesting the underlying technology of production (including degree of interdependence, uncertainty, labor intensivity, and repetition, etc.) may be an important driver of bureaucratic structuring (Child, 1973; Collins, 1975; Fuchs, 1992; Shinn, 1982; Whitley, 1984; Woodward, 1965).

This paper develops organization theories by showing that they operate even for professionals and semi-professionals in self-organized work groups (as most academic research projects are self-organized), that the size effects apply across modest increases in size, and that there is a contingency between size and interdependence, suggesting that the technology of production may be key to understanding bureaucratization and the size–structure relation (Child, 1973; Collins, 1975; Fuchs, 1992; Shinn, 1982; Whitley, 1984; Woodward, 1965).

Bureaucratic structuring may also be facilitated by such field-level characteristics as standardization of research procedures across a field and concentration of control over reputations and resources (Collins, 1975; Fuchs, 1992; Shinn, 1982; Whitley, 1984). The first allows the creation of sub-scientist specialties that can move from project to project, and the incorporation of these specialists into a more complex division of labor, while the second creates the concentration of research into larger projects around expensive equipment or major programmatic funding initiatives, further generating bureaucratic structuring. Whitley (1984) argues that, in addition to field-level differences, there may also be national-level differences in the tendency toward more or less bureaucratic structuring, using the example of the 19th Century Prussian chair system and the contemporary American university system (see also Hollingsworth, 2006). There may also be country-specific environmental factors, such as those required to deal with IRB, export control, funding agency reporting, etc., that impose standardized procedures and generate new specialties in the division of labor through a process of coercive or normative isomorphism (DiMaggio and Powell, 1983; Edelman, 1992). Thus, future work can compare the overall levels of bureaucratic structuring in science across countries (and over time), and also test how sensitive this structuring is to field differences and to the size, interdisciplinarity, and interdependence of the teams.

Furthermore, our results suggest that using an organizational studies lens to examine science raises significant questions with respect to the reward system of science and for an understanding of scientific careers. For example, the larger size of research groups, and the associated division of labor and standardization of work processes, may generate new specialist semi-professionals in the scientific workforce, which we have provocatively labeled as "sub-scientists". While we have observed concerns about the post-doc problem over the last decades, our results suggest that this is not just about a shortage of master-craftsman slots, but is also a result of the need to run large scale projects on increasingly bureaucratic principles, in part due to increasing pressures from the environment that controls critical resources (Hackett, 1990). However, this increase in efficiency and productivity may be in conflict with the need to provide training and task flexibility for young scientists-in-training (Hagstrom, 1964). Furthermore, there is a need to adapt university career and reward policies to this new organization of science. In the early days of this transformation, Hagstrom (1964) noted the reluctance of some universities to incorporate the new sub-scientist roles into their formal career structure. As the structures of scientific projects change, we may need a concomitant change in scientific institutions to accommodate the careers of those staffing such bureaucratized projects.

One limitation of the study is that there can be some ambiguity about the interpretations of our measures. In particular, although we interpret regular checking of lab notebooks and regular meetings as measures of standardization, it is also possible to interpret these as coordination mechanisms (Lawrence and Lorsch, 1967; Van de Ven et al., 1976). While the predictions are similar (increasing size should also increase coordination mechanisms, especially in the face of division of labor and interdependence), it would be useful in further work to see how different measures of standardization and/or coordination would be related to size. Similarly, a more robust test of hierarchy effects would be to see if the levels of hierarchy proliferate as size becomes larger, for example, by putting post-docs in supervisory roles between students and technicians on the one hand and lab heads on the other (Shinn, 1982). Thus, while our results are robust across a variety of measures, and to tests for endogeneity, future work could improve on our measures and data collection to more clearly rule out rival explanations. Similarly, our measure of interdependence is based on a dichotomy of high and low interdependency fields. Even with this crude measure, we are able to find statistically significant effects of interdependence (although we cannot rule out other explanations that are collinear with the high and low interdependence field classification). Project-level measures of interdependence, following Van de Ven et al.'s (1976) work, would help further specify the relation between forms of interdependence and the different components of bureaucratic structuring.

Our goal in this paper is both to test theories of organizations and to develop an organizational theory of science in order to better understand the institution of science. These findings may provide an opportunity for opening new research areas and examining new research questions related to the sociology and economics of science. We suspect that this bureaucratization of science will generate self-reinforcing feedback mechanisms that both change the career possibilities of scientists and provide the structures in which these new types of science-related occupations can be employed. Similarly, the changing organization of scientific work groups should change the relation between scientific production as measured by authorship lists on publications and the reputations and therefore career prospects of scientists (Biagioli, 2003; Fuchs, 1992). Future work is also needed to explore how the composition of teams maps onto author lists (the issue of guest and ghost authors), and how that relates to the division of labor and other structural variables (Haeussler and Sauermann, 2013; Lissoni et al., 2010).

Finally, there is the question of the effect of these changes on productivity and creativity in science (Hargens, 1975). While division of labor has long been seen as a key driver of productivity (Becker and Murphy, 1992; Smith, 1776), there are concerns that scientific work groups made up of technical specialists organized in an elaborate and highly formalized division of labor may not be well placed to generate truly creative results (Andrews, 1976; Hollingsworth, 2004; Murayama et al., 2012). The results of such research on the links between bureaucratization and creativity in science would have important implications for organization and management theory as well, especially for studies of the management of technology or of creative occupations. Prior work on the size-productivity relationship shows mixed results (Bonaccorsi and Daraio, 2005; Wallmark et al., 1973) and points to the need to analyze collaboration structures (Carayol and Matt, 2004; Cummings et al., 2013). An analysis of the relation between hierarchy and serendipity in scientific teams finds that hierarchy is associated with greater productivity (papers produced) but lower chances of serendipitous findings (Murayama et al., 2012). However, an analysis of division of labor and creativity finds that greater division of labor is associated with more novelty in scientific papers (Lee et al., 2015). These results suggest that tracking the impact of bureaucratization on productivity and creativity in science will be a key research area for bridging organization theory and the sociology and economics of science.

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Appendix A. Journal fields and aggregated presentation fields.

Journal fields and aggregated presentation fields.

Table A1.

Table A1

ISI journal fields	Aggregate presentation fields
1. Chemistry	1. Chemistry
2. Agricultural sciences	2. Agricultural science
3. Plant & animal science	
4. Biology & biochemistry	3. Biology
5. Microbiology	
6. Molecular biology & genetics	
7. Neuroscience & behavior	
8. Pharmacology & toxicology	
9. Immunology	
10. Computer science	4. CS/mathematics
11. Mathematics	
12. Engineering	5. Engineering
13. Environment/ecology	6. Environmental/geoscience
14. Geosciences	
15. Clinical medicine	7. Medicine
16. Psychiatry/psychology	
17. Materials science	8. Materials science
18. Physics	9. Physics & space science
19. Space science	
20. Economics & business	10. Social science
21. Social sciences, general	
22. Multidisciplinary	Assigned to one of the aggregate fields based on an analysis of references in the paper

Appendix B. Question wording.

Question wording.

Table A2.

Table A2

Variable	Question	Measure
Internal DoL	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "The project involved a strict division of labor with each person responsible for a specific part of the research"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"
External DoL	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "The project involved outsourcing parts of the work to other research groups"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"

Table A2 (*Continued*)

Variable	Question	Measure
Specialist role (anytech)	The survey included the following: "Please indicate the numbers of PhD-level researchers, students and technicians who played a significant role in the implementation of the project but are not co-authors of the focal paper"	A binary variable based on whether the number of non-author technicians is greater than zero vs. equal to zero
Regular notecheck	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "The project leaders checked the graduate students' lab notebooks at least once per week"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"
Regular meeting	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "The whole research group met every week to share information on project progress"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"
Hierarchical reporting	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "There was a clear hierarchy in the research group, such that students reported to team leaders and team leaders reported to lab heads"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"
Having a manager	"Please indicate which of the following best describes your role in the management of the research project.": (1) "A leading role in the research management, designing the research project, organizing the research team, and/or acquiring research funds (Principal Investigator or Co-PI)"; (b) "A member of the research management but less than that of the leader"; (c) "No managerial role"; (d) "Management was not necessary"	A binary variable coded "1" if there is management [whether or not the respondent was a manager] (a, b, or c) and "0" if management was not necessary (d)
Decentralization	"To what extent did your research group do each of the following", with answers on a 5-point scale, from 1: not at all to 5: very much so. The question wording was as follows: "During the course of the project, graduate students developed on their own changes in the research protocol"	For the binary variable, scores of 2 and above are coded as "1" and a score of 1 is coded as "0"

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