Organizing knowledge sharing and learning: the case of a mission research agency

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Abstract

This paper extends previous models of knowledge sharing that have emphasized motivation to share knowledge, a culture of knowledge sharing, and management support by including measures of morale, risk-taking culture, management quality, and organizational opportunity to share. In the extended model, the significance of the motivational measures is reduced and the strongest predictors of sharing are qualities of management, a risk-taking culture and opportunities to share knowledge as measured by participation in teams and networks. We also look at measures of research processes; although time spent in organizational activity has a negative effect on sharing and time spent in complex research tasks has a positive effect, these effects pale compared to the effects of working on teams to solve challenging problems. These analyses are based on surveys of scientists in a government research laboratory.

Keywords

Learning, knowledge sharing, organizational culture, intrinsic rewards

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The increasing importance of innovation for economic growth and employment has led the OECD to keep innovation scorecards (http:/ec.europa.eu) and for countries such as the United States to worry about their rankings (Committee of the 2005 Report on Rising Above the Gathering Storm, 2010; Hage, 2011). Correspondingly, academics have been emphasizing the concept of innovation systems as a construct for describing and analyzing the innovation performance of different countries (Archibugi & Lundvall, 2002; Hall & Soskice, 2001; Lundvall, 1992; Nelson, 1993). As governments increase their R&D expenditures, the larger share of this frequently goes into the public sector, making this more and more a critical component of innovation systems. Within this component, an important intellectual topic is how the design of research work affects amounts of knowledge sharing and learning. Although there have been some studies of research work in academic settings (Bozeman, 2013; Bozeman & Boardman, 2004; Kim & Ju, 2008; Lee & Bozeman, 2005), we have not found any that examine knowledge sharing and learning in public sector research laboratories (see references in Argote & Miron-Spektor, 2011; Dierkes, Antal, Child, & Nonaka, 2001; Easterby-Smith & Lyles, 2003; Foss, Minbaeva, Pedersen, & Rienhold, 2009; Wang & Noe, 2010). A recent special issue of *Organizational Studies* (see Arllano-Gault, Demortain, Rouillard, & Thoenig, 2013) calls attention to the lack of studies of public organizations within journals that are concerned with organizational sociology. In agreement with them, we think that there is much to be gained by examining knowledge sharing in organizations concerned with generating knowledge.

The objective of this paper is to begin to explore the topic of how the organization of research affects knowledge sharing and learning among scientists by examining knowledge sharing in a public sector research mission agency in the United States -- the Center for Satellite Applications and Research (STAR), a part of the National Oceanographic and Atmospheric Agency (NOAA). A great deal of STAR's work relies on the use of remote sensing (satellite) data, facilitating the development of satellite instruments by NASA and creating algorithms that translate data from satellites into formats and products for use in climate and weather analysis. These products are utilized by interested parties around the world, most particularly by weather forecasters and academics in oceanography and atmospheric research. For example, STAR has developed products for measuring the thickness of arctic sea ice, predicting harmful algal blooms in the Chesapeake Bay, the size of the ozone hole in Antarctica, and detecting wild forest fires in the Amazon, among many others (Powell, Ohring, Kalb, & Goldber, 2012: 148, 98, and 120 respectively). Relative to Bozeman's (2013: 178) scale of publicness, STAR is an interesting combination that is somewhat difficult to classify. It produces products that have considerable commercial value, but these products are provided free. At the same time, STAR is concerned with expanding basic geosciences theory, such as those related to climate change. The key point is that STAR's funding comes from the Departments of Commerce and Defense, the National Aeronautics and Space Administration, and other inter-agency agreements. And while it is primarily a mission agency, STAR engages in basic as well as applied research.

Studies of knowledge exchange have tended to emphasize intrinsic vs. extrinsic motivation, supportive culture, management support, and job autonomy (Foss et al., 2009; Wang & Noe, 2010). This research study adds to the literature in the following ways. First, we expand the definition and measurement of knowledge sharing. Second, we develop the concepts and measures of motivation, supportive culture, and management support, and we provide greater specificity on research routines and participation in teams and networks. The first section develops these ideas by presenting a theoretical framework that discusses the larger propositions from which are derived specific hypotheses. In particular, we argue that it is important to understand ways in which the creation of new knowledge and applied products changes the content of knowledge. Our framework also considers the need to develop a careful consideration of the kinds of collaboration, risk-taking culture, and management qualities that are likely to generate more exchanges of knowledge. In section two, we discuss our methods and data. In section three, we present tests of our hypothesis tests, followed by discussion of the limitations of our work and conclusions that can be drawn.

Theoretical framework

Three recent reviews of knowledge sharing and learning provide a theoretical map of how our framework can be situated (Argote & Miron-Spektor, 2011; Foss, Husted, & Michailova, 2010; Wang & Noe, 2010). The reviews note various dimensions of knowledge being exchanged such as explicit versus tacit and stickiness, but none focus on the different content of the information being exchanged. In this study, we distinguish between four kinds of information exchange: (1) critical thought; (2) cross-fertilization of technical ideas, (3) communication between project members; and (4) communication between project managers and senior management. Cross-fertilization of ideas is an obvious way of learning for scientists, but less obvious is the importance of critical thought. Too much emphasis has been placed on having good ideas and not enough on how to separate what part of a good idea may be actually erroneous and needs to be rectified or discarded. This is the task of critical thought. Good communication facilitates the exchange of ideas and supports critical thought. Our argument is that the technical content in these two channels of communication is likely to be different. Nickerson and Zenger (2004) note in the discussion of a problem-solving approach to organizations that senior level managers are likely to have less expertise, but of course they are more able to align projects with the overall strategy of the organization. In contrast, the communication within a project is more likely to be the "nuts and bolts" of experiments and focused on highly specialized problems that have to be solved with tacit knowledge. We add the four kinds of content together into an index of knowledge sharing and learning. Sharing knowledge and learning is a complex process and therefore an index provides a better method for capturing this phenomenon than a single question, which tends to dominate in the knowledge sharing literature (Foss et al., 2009; Wang & Noe, 2010).

Although many studies of knowledge sharing are at the individual level, there is a desire to connect to the organizational level and argue that there are significant impacts on the products of the organization (Argote & Miron-Spektor, 2011). In the case of research scientists, each research project tends to be different and this is especially true in the case of STAR as one moves from oceanographic to atmospheric research. Even though STAR is a small research organization, there are nine research groups. This does not mean that there are not generic methods (e.g. establishing ground truth for an algorithm) or generic problems (e.g. the interaction between ocean and air), but that these are more the exception than the rule. Furthermore, the inherent evolution of scientific research is towards more and more specialized knowledge. For this reason, it is difficult to demonstrate the impact of knowledge sharing on the development of a new product. For example, which ideas lead to an insight that results in some change in a research routine? Only ethnographic research across a considerable period of time might eventually establish the sequence of information received and ideas generated, which is quite difficult. Indeed, studies of innovators in health and welfare organizations indicate that the individuals involved cannot recall the origin of their ideas (Hage, 1980).

Basic and applied scientific research routines and applied research goals

Starting with the insights of Argote and Miron-Spektor (2011) about the concepts of members, tools, and tasks, we begin by focusing on routines as a more general idea than tasks, as suggested in the work of Nelson and Winter (1982). They emphasized the importance of R&D as a major input that explained evolution but did not address the kinds of research routines in R&D. As anyone who engages in research knows, research activities include not only the actual research but also involve a number of other kinds of tasks, including the routine of technical tasks involved in data collection and storage, professional activities such as attending conferences and reviewing papers, administration and paper work not related to research, and educational outreach and public relations (see list in Figure 1). An issue is which of these tasks is more likely to stimulate the search for technical information or knowledge exchanges. Our assumption is that the main task that is likely to do this is the conduct of research. Research is by its nature a complex problem that is likely to precipitate the search for knowledge. Essentially, the reasoning is that the more complex the applied problem, the more knowledge sharing there will be (Nickerson and Zenger, 2004). The essential difference between the third and the fourth activity on the list in Figure 1 (professional tasks and organizational tasks) is between professional tasks associated with scientific research and bureaucratic responsibilities of the research organization. The amount of time devoted to various kinds of bureaucratic work should hinder knowledge exchanges precisely because it is the opposite of a complex task. We expect the other three tasks in the list to be neutral relative to exchanges.

Although we are interested in a general framework, it is at the same time important to recognize the specific objectives of the research organization, such as whether basic or applied. Other research has demonstrated that there are considerable differences in the amount of knowledge sharing by discipline (Hage, Mote, Clark, & Jordan, 2013). The same should be true for different kinds of applied goals. Certainly, one might argue that there are organizational issues that encourage knowledge sharing such as the problem of safety (Nesheim & Gressard, 2014). Some of these are likely to represent complex problems that encourage knowledge sharing. In the list of Figure 1, it is particularly numbers 3 and 4 that have enough complexity that knowledge sharing should occur. In contrast, 1 and 2 are more likely to generate self-directed learning.

The central idea can be summarized as follows:

I. The more complex the scientific problem, the more the knowledge exchanges.

[Figure 1 about here]

Research teams and network collaboration routines

If the complexity of the problem encourages exchanges of knowledge, then the nature of the research teams and kinds of networks generated provide opportunities for knowledge exchange. The importance of team problem solving was demonstrated in the pioneering work of Nonaka and Takeuchi (1995) on quality work circles. In addition, team problem solving plays an important role in the literature on the search behavior of organizations (Almeida, Phene, & Grant, 2003; Chesbrough, 2006; von Rosenstiel & Koch, 2001) and the literature on the advantages of inter-organizational networks for innovation (Meeus & Faber, 2006; Salk & Simonin, 2003; van Wijk, Van Den Bosch, & Volberda, 2003). Kim and Lee (2006) found that social networks increased knowledge sharing capabilities for IT.

The various measures of opportunities for knowledge exchange are listed in Figure 1, where distinctions are made among teams, internal networks and external networks. An important and common characteristic of research is that it usually involves working with others (Hand, 2010), but again research projects vary considerably in the amount of time spent in teams, especially in networks. An important characteristic of STAR is that a lot of its research work involves interacting with other agencies. For example, one line of research work is the design of sensors that are constructed by NASA. Another important kind of external collaboration at STAR is determining what kinds of algorithms have to be developed to satisfy the needs of the numerical weather models used by the National Weather Service (NWS). We add these three items (project teamwork, cross-project teamwork, and external collaborations) together into an index of collaboration.

In addition to constructing a collaboration index, we also explore two separate measures of opportunities for collaborations. First, we explore the number of projects. Many of the STAR researchers we investigated participated in five or more projects, which raises the question of whether the number of projects leads to more or less knowledge exchange. Second, we measure of the location of the research project. STAR has three major cooperative programs located at universities where their staff is co-located, although most of the staff is located in two separate buildings in the Washington, D.C. metropolitan area. We explore in the data analysis if location in a university setting encourages knowledge exchange and how much.

The overarching proposition that subsumes these different kinds of collaborative routines is:

II. The more opportunities for collaboration, the more knowledge exchange.

Risk-taking culture and authority to make research decisions

If the design of research work presents problems that encourage knowledge sharing and opportunities in which this can be accomplished, then the extent to which the culture of the research organization encourages risk-taking will affect willingness to do it. An important theme in the knowledge sharing literature is the idea of a supportive culture (Syed-Ikhsan & Rowland, 2004). Three research processes that are associated with innovation would appear to be a good way of providing an explicit measure of a supportive culture that would encourage knowledge exchange without asking this directly. As can be seen in Figure 1, these processes are the challenge of the research problem, encouraging creativity, and providing freedom to explore new ideas. Challenge repeats the theme of the problem of complexity leading to more exchanges, except now it is what the researchers are encouraged to do, that is, tackle difficult issues. Challenge and freedom to pursue new ideas have been suggested as a measure of a climate of organizational learning (Tetrick & Da Silva, 2003). These are all variations on the idea of risk-taking (Hage, 2011; Sicotte & Langely, 2000). But while challenge has not received the same attention in the innovation literature as creativity and freedom to explore new ideas, it is quite similar in that the assumption is that the greater the challenge of the scientific problem the greater the opportunities for learning.

Another important theme in the knowledge exchange literature is the idea of job autonomy (Moreman, 2003: 113-14). We have included it in the same section as a risk-taking culture since the ability to make one's own research decisions should increase the probability of also taking risks and thus engaging in knowledge exchanges. Closely akin to job autonomy is the idea of job design. Moreman (2003) notes that by design a job should be significant, have variety, and create an identity. We feel that these are by definition involved in research work in an agency such as STAR. Furthermore, they are very similar to our measures of a risk-taking culture since challenge implies significance, freedom to explore new ideas means variety of work, and of course, being creative should allow one to achieve a sense of identity.

The overarching proposition that subsumes these different kinds of ideas is:

III. The greater the risk-taking culture of the organization, the more knowledge exchanges.

Motivation and individual respect

Closely akin to the idea of a risk-taking culture encouraging exchanges of knowledge is the topic of the motivation to do so. Again, this has been widely studied in the literature on knowledge sharing. Here the debate has been about the relative importance of intrinsic vs. extrinsic motivation to share knowledge (see Wang & Noe, 2010). The typical argument is that intrinsic motivation is more likely to lead to exchanges of technical information (Foss et al., 2009; Nesheim & Gressgard, 2014) although the evidence for this is mixed (see review by Wang & Noe, 2010). For example, S Kim and Lee (2006) found performance-based reward systems increased willingness to share knowledge. Several lines of reasoning indicate that scientists who join STAR probably have strong intrinsic motivation. STAR is one of the few places where geoscientists can work developing applied products that improve weather prediction or save people's lives from extreme violent storms, fires, and other weather events such as flooding. All of the products of STAR are public goods, which provides its own kind of intrinsic motivation. Beyond this, job characteristics that are thought to produce high motivation such as work that creates identity, has variety, and is significant all are common on the research projects of STAR scientists (Moreman, 2003). Indeed, the dimensions of a risk-taking culture are also likely to complement intrinsic motivation.

Given the likely high intrinsic motivations of researchers in STAR, we would not expect the argument that high extrinsic motivation encourages knowledge sharing to be relevant. However, we can explore the impact of extrinsic motivations with the line of reasoning that they do facilitate knowledge exchange above and beyond that caused by intrinsic motivation. Again, problems of measurement occur because the federal civil service regulates salaries and benefits. We solve this problem by including three other measures of extrinsic rewards in an index of extrinsic motivation: career advancement opportunities, educational opportunities, and recognition of merit. These items allow us to assess relationships between extrinsic rewards and knowledge sharing.

Apart from the relative importance of intrinsic and extrinsic motivations, a larger question is whether scientists with higher morale are more likely to engage in exchanges. This might be one way of resolving conflicting findings; namely, it is higher morale, regardless of how it is produced, that leads to more knowledge exchanges. DeVries, van den Hooff and de Ridder, (2006) found that job satisfaction was positively associated with both a willingness to share knowledge and an eagerness to do so in a path model where the latter two attitudinal variables explain knowledge sharing behavior. In this study, a job satisfaction index with the research environment is constructed that includes not only current satisfaction but also perceived trends in the research environment. Given the debates about federal funding of research, this is an important qualification for morale in a public mission agency. As still another measure of morale, we include a single item on the amount of respect received by an individual, a measure found in previous research to be especially sensitive (Mote, Hage, & Hadden, 2013). The reasoning is that as morale increases and there is more respect of the scientists as individuals, they will engage in more exchanges. Higher morale or *esprit de corps* implies a greater concern about others and a willingness to exchange knowledge with them for the collective benefit. Wang and Noe (2006) in their review of the cultural differences in exchanging knowledge among Americans and Chinese found support for this, although there are differences in the way in which the collective is defined by these two ethnic groups.

The overarching proposition combines the basis of motivation, intrinsic versus extrinsic, with actual measures of the level of morale; it is:

IV. The higher the morale, the more knowledge exchanges.

Managerial quality

An additional important theme in the knowledge sharing literature is the role of managers. Usually, this is measured with questions on the extent that managers encourage sharing. We propose instead to focus on those kinds of managerial behaviors that we think will create an organizational atmosphere for knowledge sharing. Foss, Husted and Michailova (2010) argue that it is important to expand the understanding of governance and its impact on knowledge sharing. One way to begin this process is by expanding the measured qualities of management beyond the simple idea of encouraging knowledge sharing. Another reason to expand the measures of management quality is the observation by Wang and Noe that (2010) that leadership quality is an understudied area.

As can be observed in Figure 1, we perceive three characteristics of managers to be important: the integrity of managers, how well informed managers are, and finally the idea that managers add value to the research project. The integrity of managers is likely to create an atmosphere of trust, which is an idea stressed in the knowledge sharing literature. Clearly how well informed managers are and their ability to add value should also encourage knowledge sharing. Our larger argument is as follows:

V. The higher the perceived quality of managers, the more knowledge exchanges.

We have made five general arguments about the causes of knowledge exchanges: the complexity of problems, structural opportunities for knowledge sharing, a culture of risk-taking, motivations to share, and managerial quality. In each instance, the constructs have multiple measures, allowing us to build upon and extend the existing literature. From these general arguments a series of specific predictions can be made.

Predictions

We developed a number of hypotheses that reflect our five general propositions. The first general proposition is:

Proposition I. The more complex the scientific problem, the more the knowledge exchanges.

We derive the following hypotheses:

1a: The more time devoted to conducting fundamental research, the greater the amount of knowledge exchanges.
1b: The more time devoted to organizational tasks, the fewer knowledge exchanges.
1c: The amount of time devoted to routine technological tasks, professional tasks, and outreach tasks will have no effect on the amount of knowledge exchanges.
1d: The amount of time to find errors in satellite data or improving algorithms for translating satellite data will have no effect on the amount of knowledge exchanges;
1e: The more time reviewing the design of sensors to be placed on satellites, the greater the amount of knowledge exchanges;
1f: The greater the amount of time reviewing predictive models in either weather prediction or science, the greater the amount of knowledge exchanges.

The connection between the general proposition and these hypotheses is that more complex problems necessitate seeking out new information and expertise from others.

Proposition II. The more opportunities for collaboration, the more knowledge exchanges.

From this proposition, we have the following hypotheses:

2a: The more often scientists report project teamwork, the greater the amount of knowledge exchanges.
2b: The more often scientists report internal collaborations, the greater the amount of knowledge exchanges.
2c: The more often scientists report external collaborations, the greater the amount of knowledge exchanges.
2d: The greater the number of research projects, the greater the amount of knowledge exchanges.
2e: Scientists located in universities are more likely to exchange knowledge than scientists located at STAR headquarters.

Again, the connection between the general proposition and these hypotheses is the variety of ways in which structural opportunities for collaboration can be created.

The third proposition attempts to measure processes that encourage knowledge sharing.

Proposition III. The greater the risk-taking culture of the organization, the more knowledge exchanges.

From this proposition, we derive the following hypotheses:

3a: The greater the extent to which scientists agree there is a sense of challenge in their workplace, the greater the amount of knowledge sharing.

3b: The greater the extent to which scientists agree that people in their agency have time to think creatively, the greater the amount of knowledge sharing.
3c: The greater the extent to which researchers agree that there is freedom to pursue new ideas, the greater the amount of knowledge sharing.
3d: The greater the extent to which researchers agree that they are involved in the decisions about the course of their research work, the greater the amount of knowledge sharing.

As indicated above, the connection between these four hypotheses and sharing knowledge is the idea that risk-taking encourages seeking new knowledge and also implies more complex problems.

The fourth proposition moves from a cultural basis for exchanges of knowledge to a motivational one:

Proposition IV. The higher the morale, the more knowledge exchanges.

From this proposition, we derive the following hypotheses:

4a: The more often scientists report they receive comparable salaries and benefits, the greater the amount of knowledge sharing.
4b: The more often scientists report that there are career advancement opportunities, the greater the amount of knowledge sharing.
4c: The more often scientists report that there are educational opportunities, the greater the amount of knowledge sharing.
4d: The more often scientists report that there are rewards for merit, the greater the amount of knowledge sharing.
4e: The more often scientists report that the research environment is good and improving, the greater the amount of knowledge sharing.
4f: The more often scientists report that there is respect for them as individuals, the greater the amount of knowledge sharing.

Besides a culture of risk-taking and the motivations that encourage knowledge sharing, another important issue is how the quality of the manager affects exchanges of technical information. Our last proposition is:

Proposition V. The higher the quality of managers, the more knowledge exchanges.

5a: The more often scientists report management has integrity, the greater the amount of knowledge sharing.
5b: The more often scientists report that management is informed, the greater the amount of knowledge sharing.
5c: The more often scientists report that management adds value, the greater the amount of knowledge sharing.

These 24 hypotheses allow us to extend the literature on knowledge sharing and in particular make it highly relevant for the study of scientists doing research.

Methods

The primary data used to test our hypotheses come from a survey designed specifically for research organizations and scientists. The survey was developed through an extensive literature review and with input from 15 focus groups that included bench scientists, engineers and technologists, as well as their managers, across various R&D tasks, and it has been field-tested in a number of research organizations (Jordan, 2005; Jordan & Streit, 2003; Jordan, Streit, & Binkley, 2003).

The data on STAR were collected in three waves, each two years apart, in 2005, 2007, and 2009. The response rates were respectively 79 (n = 58), 56 (n = 44), and 50 percent (n = 31). All scientists working at STAR were invited to participate. The decline in the number of scientists reflects the impact of retirements and the gradual movement of more and more work into contracts with private contractors. It is more difficult to explain the declining response rate, but it may be due to survey fatigue in successive waves. In a study of the same organization where waves are pooled, there is some concern about potential serial correlation because individuals responded in multiple waves. Given civil service concerns, identifiers were not collected, so it is not possible to link records across waves; however, we did ask respondents if they had completed earlier versions of the survey. The 133 respondents represent 84 distinct individuals, and only one-third of the respondents in the third wave had responded in both earlier waves. Furthermore, there is a two-year interval between waves. Finally, we would argue that the changes in the mean scores on various components of the knowledge sharing index suggest there should be little concern about serial correlation. Indeed, the more critical problem is how much the changes in the key dependent variable might explain support for some or all of the hypotheses. But to be sure there were not problems associated with when the data were collected, we also control for wave in the final tables.

After entry into a computer, the data were edited and corrected. Incomplete questionnaires were completed with an iterative regression procedure (Raghunathan, Lepkowski, Van Hoewyk, & Solenberger, 2001); 2.3 percent of the data values were missing. This, and the statistical analyses, was done with R software (R Core Team, 2012). The differences between correlation coefficients were tested with the psych package of R (Revelle, 2012).

Measuring the content of the knowledge exchanges

In the framework, we suggested that it was important to construct indices of four kinds of content involved in knowledge sharing. This approach suggests that when sharing knowledge there are advantages of having different kinds of content. Cross-fertilization and critical thought are quite distinct and yet both are useful. The two communication variables also differ in content because of their location. Communication within a project is likely to include sharing tacit knowledge whereas communication with managers and senior managers is more likely to be strategic in nature.

For each type of knowledge exchange content, scientists were asked to report what percent of the time it was true in five categories: 0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81% to 100%. The means for each wave are reported in Table 1, where 3 represents 41 to 60% of the time. Critical thought increases from 3.67 in 2005 to 4.07 in 2007 but then declines to 3.58 in 2009 while cross-fertilization also increases slightly from 3.05 to 3.38 across the three waves. Communication on projects increases in each wave and communication with management increases from 2005 to 2007. Combining these, the index of knowledge exchanges increases from 2005 to 2007 and again to 2009. Given the small sample size, however, these differences are not statistically significant. The index of knowledge exchanges is constructed by standardizing each of the four components and then adding them together, then the index is rescaled to range from 1 to 5 to make it comparable to the constituent items. Cronbach's alpha for the index is 0.80.

[Table 1 about here]

Despite this high level of internal consistency, in the first phase of the analysis we report zero-order correlations testing the hypotheses with each measure of the content of the knowledge exchange as well as the knowledge sharing index. The analysis provides some insights into when critical thought is maximized as distinct from cross-fertilization, which is the more commonly reported measure of knowledge sharing. It should be emphasized that we are not measuring organizational learning but instead the sharing of individual scientists in what might be called an organization dedicated to applied learning.

Measuring organizational context

To explore the relative importance of these different ways of describing the organizational context, we constructed indices that add the various attributes together as indicated in Figure 2. We experimented with constructing an index combining the amount of time spent on fundamental research with the objective of reviewing models, but this did not explain much variation and in the multivariate analysis its effect approaches zero; therefore it is not reported here. However, in the multivariate analysis we report the single items.

As above, each item in the index is measured by asking the scientists to report what percent of the time it is true in five categories: 0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81% to 100%. The Cronbach alphas for two of these indexes are somewhat low, collaboration and risk-taking culture, but a factor analysis confirmed that the individual items load satisfactorily on a single dimension. These indices do not include all the items that have been discussed. We did not include number of projects nor location in a university with the network and collaboration index because their substantive meaning is quite different. The same is true for job autonomy not being combined with a risk-taking culture. Obviously morale and respect as an individual are quite different from material rewards.

[Figure 2 about here]

Research findings

The findings are reported in three sub-sections, the first of which examines the predictions about the 11 hypotheses exploring the design of research work and each of the kinds of content in knowledge sharing as well as the index. Here the issue is how much the complexity of the problem and opportunities for sharing knowledge encourage one or another kind of knowledge sharing as well as the total amount. The second section considers the impact of kind of motivation, risk-taking culture, and management quality on knowledge sharing; that is, the other 13 hypotheses. These two analyses allow us to understand if there are any interesting substantive differences between specific indicators and their relationships with each knowledge content mechanism and with the index of knowledge sharing. By isolating which indicator is most important, one can provide advice to research managers and also understand better the third analysis, which is multivariate.

Consistent with the above division, we report three models: (1) the different ways of describing the complexity of the problem and opportunities for sharing; (2) motivation, risk-taking culture, and management quality; and (3) all five general arguments. In the multivariate analysis, we also control for the wave in which the data were collected to be sure that it is not an artifact of when the survey was distributed. In fact, there are some significant effects attached to wave in 2009.

Basic and applied scientific research routines, goals, collaboration and knowledge exchanges

The surprising complexity of research work is readily observable in Table 2(a), where the scientists in STAR have indicated the amount of time they allocate to five research tasks (we have ignored the other category). Of these five, only research for fundamental understanding has a significant positive impact on three kinds of knowledge exchanges and the index. The small but non-significant relationships of the other tasks, except for organizational work, are to be expected because it is basic research that is most specifically orientated towards the scientific learning that we have measured. Perhaps the most interesting finding is that organizational tasks such as managing contractors and paperwork that are bureaucratic requirements because STAR is part of a larger organization (NOAA) have a significant *negative* relationship to two kinds of knowledge exchanges and in particular communication between management and senior management as well as the knowledge exchange index. Indeed, the negative impact of organizational tasks is greater than the positive impact of spending time in fundamental research. Thus, hypotheses 1a, 1b and 1c are partially supported.

As we have indicated, the applied research of STAR has four distinctive applied research goals. As can be seen in Table 2(b), only one of these specific objectives, namely the review of models, leads to knowledge exchanges and then only with cross-fertilization and within-project communication. Contrary to our hypothesis 1d, reviewing the design of sensors does not produce knowledge exchanges as we have measured them. The larger conclusion to draw from this table is that most of the associations between the applied research goals and the various components of learning are essentially zero. Given the lack of a relationship between reviewing models and critical thought, hypothesis 1e is only partially supported. For the larger issue of does the complexity of problems lead to more knowledge exchanges, the answer is a somewhat weak yes.

[Table 2 about here]

If the zero-order correlations in Table 2(a and b) are relatively weak or non-existent, quite an opposite picture emerges in 2(c). Opportunities for exchanges are a much more important stimulant than the complexity of the problem. Teamwork and internal networks both have very strong zero-order correlations with each kind of knowledge sharing content and the index of knowledge exchanges. In contrast, the relationships are less strong with external networks. This reflects the fact that not all of the scientists are involved in external relationships.

In the theoretical framework, we stressed the importance of the content of critical thought. As we observed in Table 2(a), only fundamental research has a weak relationship to this kind of knowledge exchange. In Table 2(c), we find that it is particularly teamwork and internal networks that appear to be associated with critical thought, with correlations of .34 and .33 respectively. The difference between the first and second indicator of opportunities for knowledge exchanges is between collaboration within the same research project and collaborations with researchers in other projects within the same organization. But the really strong relationships are with the other three kinds of content, especially when one examines the collaboration index in the middle row of Table 2(c). Opportunities for knowledge exchanges encourages cross-fertilization and communication both within the project and between management and senior management. The zero-order correlation between the two indices is quite high, .68. Hypotheses 2a, 2b, and 2c are thus supported. But neither the number of projects nor the location of the STAR scientists in universities has much impact on either the content of the knowledge exchange or the index. Thus hypotheses 2d and 2e are not supported.

Risk-taking culture, motivation, management quality and knowledge exchanges

If having opportunities increases the amount and types of knowledge exchanges, so does the presence of a risk-taking culture (see Table 3(a)). *Of these three indicators of a risk-taking culture, it is challenge that has by far the strongest impact on learning.* It has a strong association with each kind of knowledge exchange; the correlations are above 0.40 with each indicator and 0.56 with the index. Although not as strong, freedom to explore new ideas also impacts on critical thought (r = 0.36) and two of the other three kinds of knowledge exchanges, only being somewhat weak with communication within the project (r = 0.19). Surprisingly, at least for us, it is creativity that has the weakest association of the three. The index of a risk-taking culture has a parallel impact with each of the four kinds of exchanges and is strongly related to the index of knowledge exchanges, r = 0.54. This has interesting implications for managers of research projects. It suggests that one learns more by tackling difficult problems than by engaging in incremental or normal science. The three hypotheses, 3a, 3b, and 3c, are thus supported. When compared with the relatively meager findings about the nature of research, these findings lead to us to a critical conclusion. *It is not the time spent on fundamental or basic research or the specific applied research goals but instead what is done during the time available that simulates knowledge exchanges and learning*.

The measure of research autonomy also has a significant correlation with each kind of knowledge exchange and to the index (Table 3(a)). Again for managers of research projects, perhaps the most interesting finding is the strong association between making one's own research decisions and critical thought. It also has a strong association with the communication between managers and senior managers as well as with the index (r = .45). Hypothesis 3d is thus supported.

Given the inconsistent results regarding intrinsic vs. extrinsic rewards on knowledge sharing, it appears prudent to consider a variety of measures of the latter as well as separate measures of morale. The first four indicators of extrinsic rewards reported in Table 3(b) suggest the value of this approach. With federal civil service regulations largely controlling salaries and benefits, we find it has a weaker association than the other three indicators. Relative to the important content of critical thought, there is a steady progression across the four indicators with recognition of merit stimulating the most critical thought (r = 0.41). In contrast, for cross-fertilization there is not much difference across the four ways of measuring extrinsic rewards with r varying between 0.23 and 0.26. The single indicator of material rewards with the strongest impact on knowledge sharing is recognition of merit; it impacts on both communication with the project and communication between managers and senior management as well as the index of exchanges, r = 0.50. Clearly extrinsic rewards encourage knowledge exchanges of various kinds. The index of extrinsic rewards has a robust association with each of the four kinds of knowledge exchanges and especially both communication within the project and communication between management and senior management. The two indices have a zero-order correlation of 0.52. This finding is more general than the one reported in this literature because it is not specifically measuring rewards for knowledge sharing.

[Table 3 about here]

Our measure of morale also is strongly associated with critical thought (r = 0.46) and with cross-fertilization (r = 0.46) as well as the index of knowledge exchanges. Of course, it is not possible to know how much morale is created by material rewards and how much by intrinsic motivation and therefore there is presumably some overlap between these two measures. Our single indicator of respect as an individual indicates that it has the same pattern as recognition of merit. Hypotheses 4a through 4b are supported.

The last construct reported in Table 3(c) is the three indicators of management quality. All of them have very strong associations with each of the four kinds of content in the knowledge exchanges, that is above 0.40, except for the relationship of management adds value with communication within the project. The three indicators have a particularly strong association with the index of knowledge exchanges, 0.59 for integrity, 0.68 for informed, and 0.64 for adds value. The two indices, management quality and exchanges, have a very robust r = 0.71. Again, since this finding is not based directly on whether management is encouraging exchanges, it is a much more general one. Hypotheses 5a through 5c are supported.

In summary, the indices measuring opportunities to exchange, a risk-taking culture with extrinsic rewards and high morale, and management quality all have a correlation above .50 with knowledge exchanges and thus by implication learning at the level of the individual scientist. The only weak findings with some hypotheses not supported are those concerning the allocation of time to various activities and applied goals. Another way of summarizing these findings for the benefit of managers concerned with increasing a particular kind of knowledge exchange is to examine indicators with correlations above .40. The variables that increase critical thought by this standard are challenge, job autonomy, morale, and all three indicators of management quality. Cross-fertilization is stimulated by internal networks, challenge, morale and again the three measures of management quality. The variables that increase communication within the project are teamwork, internal and external networks, challenge, career advancement opportunities and recognition of merit, and respect for the individual, but only two indicators of management quality, integrity and informed. Finally, communication between management and senior management is associated with both teamwork and internal networks, challenge and job autonomy, career advancement opportunities, recognition of merit, morale, respect as an individual, and all three indicators of management quality. A remaining issue is to determine which of these indices is most important in a multivariate analysis.

The relative importance of collaboration, risk-taking culture, morale, and management quality for knowledge exchanges

Foss, Husted and Michailova (2010: 469) argue that it is important to determine the relative contribution of various factors associated with knowledge exchanges. Three models are reported in Table 4. Model 1 represents the usual explanations for knowledge exchanges such as motivation, risk-taking culture, and management along with our additional measures. Model 2 reports the impact of time spent on research, applied goals, and the various measures of opportunities for knowledge exchange. The combination of these two sets of factors is reported in model 3.

[Table 4 about here]

Some of the reasons why motivation might have inconsistent associations with knowledge exchanges are apparent in model 1. All of the different measures--the index of extrinsic rewards, respect, and morale have non-significant partials with the index. In contrast, it is only a risk-taking culture and management quality that have significant relationships. It is also worth noting that autonomy to make decisions about research is non-significant as well. Relative to our attempts to extend the existing literature it would appear that both a risk-taking culture and management quality can facilitate knowledge exchanges.

Model 2 explores the new variables that we have added to this discussion. Both waves have significant partials. As one might expect time spent in research and focusing on the reviewing of models are not significant. But unexpectedly in a multivariate context, time spent on organizational tasks has a significant, albeit small, negative relationship with knowledge exchanges. The main variable in this model is the extent of teamwork and collaboration.

Model 3 combines these various explanations and indicates that the two most important variables are collaboration and management quality. The third most important is a risk-taking culture. Finally, and somewhat surprisingly, university location is significant as well. In other words, the influence of university location on knowledge sharing only becomes apparent after one controls for the ways in which those associated with universities are different from those who are not; in particular, those in universities have lower autonomy and morale but enjoy greater respect and rewards and spend more time in research. By themselves these differences are small and not significant, but the multivariate model captures their cumulative effect. The adjusted R-square is quite robust at 0.717 or about seventy percent of the variance is explained in this model.

Conclusion and discussion

The study of how applied scientists in a public mission agency share knowledge creates some new and interesting questions. This new context highlights the advantages of exploring the different types of knowledge shared. In this circumstance and precisely because the survey instrument was developed with the aid of focus groups of scientists, we have emphasized four kinds of content: critical thought, cross-fertilization, communication within projects, and communication between management and senior management. We have suggested that tacit knowledge is more likely to be exchanged in communication within projects, but future research needs to verify this assumption. More importantly, we have argued that there is a fundamental difference between critical thought and cross-fertilization of technical information and that the former needs to be studied more, especially in the context of an organization dedicated to producing new applied knowledge. The different patterns of findings as to which variables have the most impact on what kind of knowledge exchange substantiate the advantages of our strategy of considering disparate kinds of exchanges. One important finding is how important challenge is for each of kind of knowledge exchange.

A key question is how knowledge sharing relates to organizational learning. As was explained at the beginning of this paper, the nature of research projects is differentiated kinds of knowledge. Even a small research organization such as STAR has nine research groups, and while there are some generic problems and methods, the reality is that knowledge is highly specialized and becoming more so over time as problems become more and more difficult to solve. Thus the exchanges of knowledge at best lead to learning upon the part of the scientists but seldom by the organization unless it is a joint project that involves many of the scientists. These exist but are rare. However, the pattern of individual learning as distinct from organizational learning is more and more an accurate description of what is happening in many organizations as they engage in research. Beyond this, the familiar distinction between production, marketing, purchasing, accounting, etc. and the like indicates that even in firms without R&D departments there is a considerable amount of specialized knowledge.

Although we began this paper with the assumption that spending more time on fundamental research was likely to lead to more knowledge sharing, at least in research organizations, this has not been substantiated. Rather than spending more time on research, what appears to be more central is having more opportunities to share knowledge such as working in teams, internal organizational networks, and external networks. In the multivariate analysis, opportunities to share knowledge is the single most important variable, although management quality is almost as important. It is not very startling to say more opportunities to share knowledge leads to more knowledge sharing, but it is also important to recognize how this has been measured by participation in teams and networks. Although location in a university did not have a significant zero-order correlation with knowledge sharing, it did become important in the final multivariate model. Another non-finding that surprised us was the lack of association between the number of projects and any kind of knowledge exchange, suggesting again it is how one participates in these projects that is the most critical determinant.

Previous literature has emphasized motivation to share knowledge, a culture of sharing knowledge, and management support for this. Our research has attempted to broaden this model by considering not only extrinsic rewards but also the level of morale and its effects. By themselves these motivational factors are important but they disappear in the context of a risk-taking culture, management quality, and opportunities to share knowledge as measured by participation in teams and networks. Our three measures of a risk-taking culture--challenge, creativity, and freedom to explore new ideas--provide managers with various ways in which to intervene to improve knowledge sharing in their organizations. We have already observed the importance of challenge for stimulating critical thought. Last but hardly least, management quality appears to be almost as important as opportunities to share. It has a profound effect and on all four kinds of knowledge exchanges.

These findings need to be replicated among geophysicists in other research organizations than STAR (NOAA itself has a number of other research entities) and among other broad disciplines because one could easily imagine that knowledge exchanges vary considerably. Regardless of this variation, knowing how to increase the amount of scientific exchanges is important and especially in the context of public research organizations, such as STAR, dedicated to creating new services for the benefit of society. Given the innovation crisis in the United States and the importance of STEM workers, this is a critical kind of research (Atkinson & Ezell, 2012; Estrin, 2008; Hage, 2011; Kao, 2007; Committee of the 2005 Report on Rising Above the Gathering Storm, 2010).

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Table 1. Mean time expenditure score by wave and exchange content.

Year	Exchange Content and Index of Knowledge Exchanges--Means[a]				
	Critical Thought	Cross-fertilization	Communication in projects	Communication with senior management	Index of Knowledge Exchanges
2005	3.67	3.05	3.81	3.12	3.33
2007	4.07	3.16	3.98	3.55	3.55
2009	3.58	3.38	4.16	3.52	3.52

a. Scientists reported the actual percent time that they spent in each of these five activities plus an other category that few selected.

Research Routines and Applied Research Goals	
Research Activities:	Applied Research Goals
Routine research tasks	Finding errors in data;
Fundamental research	Improving algorithms;
Professional tasks	Reviewing designs of sensors
Organizational tasks	Reviewing predictive models
Outreach tasks	
Teamwork and Network Collaboration Routines	
Teamwork and Collaboration Activities	Other Measures
Extent of teamwork	Number of projects
Extent of internal collaborations	Location in a university
Extent of external collaborations	
Index of teamwork and collaborations	
Risk-taking Culture and Autonomy to Make Research Decisions	
Risk-Taking Culture	Other Measures
Challenge	Job autonomy
Creative	
Freedom to explore	
Index of risk-taking culture	
Motivation and Individual Respect	
Extrinsic Motivation	Other Measures
Salaries and benefits	Morale (job satisfaction plus trend)
Advancement opportunities	Respect as an individual
Educational opportunities	
Rewards for merit	
Index of material rewards	
Managerial Quality	
Integrity	
Informed	
Adds value	
Index of managerial quality	

Figure 1. Independent variables and indices.

Construct	Indicators[a]	Cronbach alpha
Collaboration	Project teamwork	.66
	Cross-project teamwork	
	External collaborations	
Extrinsic rewards	Salaries and benefits	.80
	Advancement opportunities	
	Educational opportunities	
	Rewards for merit	
Risk-taking culture	Sense of challenge	.66
	Time to think creatively	
	Freedom to explore new idea	
Management Quality	Integrity	.89
	Informed	
	Adds value	

Figure 2. Indices describing four constructs measuring organizational context.

Table 2. Zero-order correlations between research activities, goals, collaboration with exchange content and an index of knowledge exchanges.

	Critical Thought	Cross-fertilization	Communication in projects	Communication with management	Index of Knowledge Exchanges
(a) Time in research tasks[a]					
Routine technical	-0.02	0.06	0.02	0.12	0.06
For fundamental understanding	0.20*	0.21*	0.04	0.21*	0.21*
Professional work	-0.02	0.07	0.13	0.08	0.08
Organizational work	-0.15	-0.26**	-0.10	-0.29***	-0.25**
Education, outreach	0.07	0.09	-0.07	0.06	0.05
(b) Applied research objectives[b]					
Causes of errors	-0.09	-0.04	-0.01	-0.01	-0.05
Improve algorithms	-0.04	-0.09	0.03	-0.05	-0.05
Review sensor designs	0.00	-0.12	-0.05	-0.10	-0.09
Review models	-0.01	0.27***	0.20*	0.13	0.19*
(c) Teamwork and collaboration[c]					
Project teamwork	0.34***	0.38***	0.68***	0.46***	0.59***
Collaborative networks	0.33***	0.56***	0.45***	0.49***	0.58***
External networks	0.20*	0.28**	0.42***	0.37***	0.40***
Index of collaboration	0.38***	0.53***	0.67***	0.57***	0.68***
Number of projects	0.15	0.14	0.11	0.04	0.14
University location	0.08	0.16	0.14	0.01	0.12

* p < .05, ** p < .01, ***, p < .001

a. Scientists reported the actual percent time that they spent in each of these five activities plus an other category that few selected.

b. Five cases that reported spending 0% of their time in fundamental research are excluded from this panel.

c. All indicators measured with the following five-point scale as percent of time: *0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81 to 100%.* NA was also an option.

Table 3. Zero-order correlations between motivation, risk-taking culture, management quality with exchange content and an index of knowledge exchanges.[a]

	Critical Thought	Cross-fertilization	Communication in projects	Communication with management	Index of Knowledge Exchanges
(a) Risk-taking culture and job autonomy					
Challenge	0.47***	0.46***	0.41***	0.44***	0.56***
Creativity	0.23**	0.19*	0.13	0.33***	0.28**
Freedom to explore	0.36***	0.33***	0.19*	0.40***	0.41***
Index of Risk-taking	0.46***	0.43***	0.32***	0.50***	0.54***
Job autonomy	0.46***	0.25**	0.27**	0.43***	0.45***
(b) Motivation					
Salaries and benefits	0.18*	0.23**	0.33***	0.21*	0.30***
Career advancement	0.28**	0.25**	0.42***	0.45***	0.44***
Education opportunities	0.39***	0.25**	0.42***	0.45***	0.41***
Recognition of merit	0.41***	0.26**	0.45***	0.46***	0.50***
Index extrinsic rewards	0.40***	0.31***	0.49***	0.46***	0.52***
Morale	0.46***	0.46***	0.32***	0.46***	0.54***
Respect as individual	0.40***	0.25**	0.43***	0.45***	0.48***
(c) Management quality					
Management integrity	0.50***	0.44***	0.42***	0.51***	0.59***
Management informed	0.51***	0.53***	0.46***	0.67***	0.68***
Management adds value	0.56***	0.47***	0.39***	0.60***	0.64***
Index of quality	0.58***	0.53***	0.47***	0.66***	0.71***

* p < .05, ** p < .01, ***, p < .001

a. All indicators measured with the following five-point scale as percent of time: *0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81 to 100%.* NA was also an option.

Table 4. Multivariate regression of indices of motivation, risk-taking culture, management quality, research tasks and goals, collaboration and location on an index of knowledge exchanges.

	Model One	Model Two	Model Three
(Intercept)	0.249	0.637*	-0.414
Year2007	0.071	0.323*	0.138
Year2009	0.184	0.404**	0.288*
Respect	0.109		0.021
Job Autonomy	0.072		0.099
Morale	-0.074		-0.077
Extrinsic rewards	0.115		-0.017
Risk-taking culture	0.255***		0.188**
Management quality	0.458***		0.414***
Number of projects		0.029	0.008
Research task		0.008	0.000
Organization task		-0.007*	-0.002
Review models		0.000	-0.002
Collaboration		0.700***	0.481***
University		0.103	0.303*
Adjusted R sq.	0.547	0.559	0.717