Research Policy 43 (2014) 349–366

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Balancing breadth and depth of expertise for innovation: A 3M story

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ARTICLE INFO

Article history:
Received 5 March 2012
Received in revised form
12 September 2013
Accepted 20 October 2013
Available online 23 November 2013

Keywords:
Innovation
Expertise and knowledge
Research and development

ABSTRACT

This study examines how inventors' breadth and depth of expertise influence innovation in 3M, a company renowned for sustained innovation for over a century. While prior research tends to examine a single indicator – the technical success achieved by the inventor – our study differentiates between three indicators of a successful inventor: (1) the number of inventions generated; (2) the extent to which the inventor has a significant impact in his or her technical domain; and (3) the inventor's career success, in terms of the commercial value they have brought by converting their inventions into products that generate sales for commercial organizations. We found that breadth of inventor expertise relates to the generation of many inventions, but not necessarily to those that are technically influential. Depth of inventor expertise enables individuals to generate technically influential inventions, as measured by patents granted. However, both breadth and depth of expertise are required for innovators to be deemed highly valuable, based on their records of effectively converting inventions into commercially successful products. Our study extends prior research on innovation in two ways. We provide a comprehensive view of how inventors' expertise influences innovation and also show how inventors with different expertise profiles can contribute in unique ways to their organization.

1. Introduction

Management scholars have extensively examined what affects innovation in organizations, especially in research and development (R&D) departments, whom companies depend on for inventions that can be translated into new products for the firm (e.g., Collinson and Wang, 2012; den Hond, 1998; Schmickl and Kieser, 2008). There are, however, still many fundamental questions for which we do not have answers. Our study focuses on two of these questions: (1) How does the breadth and depth of expertise of individual inventors influence their approach toward innovation; and (2) How does that, in turn, affect the value and contribution that inventors with different expertise profiles bring to the firm.

Innovation has been defined in many ways, with a common theme of building on existing knowledge and recombining past ideas and artifacts (Hargadon, 2002). Schumpeter (1934) defines innovation as the process of generating novel combinations from existing resources and ideas. This Schumpeterian view of innovation emphasizes how new ideas are built from existing ones. An individual's expertise is thus critical in helping individuals to generate new knowledge and to create recombinations based on existing information, as existing ideas are changed and recombined to create innovative applications (Glynn, 1996; Mumford, 2000).

Even though many inventions are created when individuals work in teams (Jones et al., 2008), studies allude to the observation that individuals are effective in combining existing knowledge to generate new knowledge and innovations (Gupta et al., 2006; Taylor and Greve, 2006). As highlighted by Crossan et al. (1999), innovative ideas and insights first occur to individuals, before such ideas are subsequently shared at the group levels and institutionalized at the organizational level. Fundamentally, this highlights that individuals are the basic unit in which knowledge integration and knowledge creation takes place, regardless of whether individuals work alone or in teams. Hargadon and Sutton (1997) further make the point that individuals are able to generate innovative creations when they effectively transform and recombine knowledge and information that they obtain from different domains. In their study of teams involved in the creation and publishing of comic books, Taylor and Greve (2006) also found that individuals were able to combine knowledge more effectively than teams.

The notebooks of Thomas Edison, one of the world's greatest inventors, show that he often recombined existing ideas in novel ways (Budline et al., 1995). For example, Edison recombined ideas from both the telegraph and the telephone transmitter to generate

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0048-7333
http://dx.doi.org/10.1016/j.respol.2013.10.009

a new idea that led to the invention of the phonograph. He realized that a vibrating needle point would leave indentations on a piece of paper (features of a telegraph) – the indentations could then be played back (features of a telephone transmitter) (Woodside, 2007). By changing paper to tin foil, he generated an invention where human voice would vibrate a diaphragm, moving a stylus which leaves grooves on the tin foil. When the machine is returned to the starting point, the grooves cause the diaphragm to vibrate again, reproducing the original sound. As this example shows, transformation and combination of ideas often occur within individual actors, demonstrating that individuals, on their own, transform and add value to ideas.

Despite the important role that individuals play in recombining existing knowledge to generate new ideas and inventions (Glynn, 1996), little research has directly explored how the expertise profiles of inventors influence the way that they approached the innovation process and how that affects the value that inventors bring to the firm (Gruber et al., 2012). Prior research has examined and found that firms and teams that are effective in integrating diverse expertise possessed by individual specialists tend to perform better (Rulke and Galaskiewicz, 2000; Tiwana and McLean, 2005; Wu and Shanley, 2009). There has, however, been limited number of studies directly examining the impact of breadth and depth of inventor expertise at the individual level, on innovation outcomes. Part of the reason for this lack of attention may be an implicit assumption that there is no question to be resolved.

One often assumes that specialization is a requirement for inventions to happen. For example, studies have regarded inventors to be knowledgeable in a domain area as long as inventors have filed at least one patent in the area (Melero and Palomeras, 2013). This implies that a certain depth of knowledge is required before someone can generate an invention. On the other hand, studies have also highlighted that breadth of expertise is useful in providing the ability to integrate diverse ideas to generate new ones. The literature on network analysis, for example, has studied how individuals' position in the social and/or knowledge structure influence their access to diverse information and thus their ability to generate new ideas (Burt, 2004; Fleming et al., 2007; Obstfeld, 2005). This literature suggests that individuals who have access to diverse information are able to generate more good ideas by combining diverse information.

Hence, one can conclude from prior research that depth and breadth of expertise are important in different ways. Yet past research has only examined breadth and depth of expertise as a single dimension at the individual level, when examining its impact. For example, Leahey and Hunter (2012) examined the impact of specialization on lawyers' earnings, and found that lawyers who specialized earned more. Leahey et al. (2010) found that specialization increased the propensity of academics in the sociology domain to obtain tenure, due to the improved productivity and visibility. Recent research appears to recognize that breadth and depth of expertise can have different impact, but has chosen to examine how the diversity and depth of knowledge drawn upon at the patent level influenced the impact of the patent (measured in terms of the number of forward citations) (Lettl et al., 2009).

In this study, we explicitly examine how the breadth and depth of inventor expertise influence their approach toward the innovation process, and how that influences different outcomes. We focus on the examination of the breadth and depth of R&D inventor's technical expertise. Depth of expertise refers to the level of knowledge and skills (e.g. novice or expert) that an individual holds in a technical domain area. Specialization cultivates profound knowledge of an area, creating efficiency in generating repeated combinations of a narrow range of knowledge elements and deep understanding of the interconnections between them (Katila and Ahuja, 2002; Yayavaram and Ahuja, 2008). Breadth of expertise refers to the diversity in knowledge, know-how and experiences that an individual has accumulated (Fleming et al., 2007). Diversity of knowledge often generates exposure to new ideas, creating opportunities to experiment with new forms of knowledge (Katila and Ahuja, 2002; Yayavaram and Ahuja, 2008). We explicitly examine how inventors with different expertise profiles – generalists with broad expertise, specialists with deep expertise and polymaths with broad *and* deep expertise, if they exist – tend to be associated with different innovation outcomes, and how they contribute to a firm in different ways.

Examining how the breadth and depth of inventor expertise influence the value that they bring to the firm require researchers to consider the role of the organization. The organizational context – the practices of the firm, and the ways that an organization support inventors with different expertise profile – would influence the firm's ability to leverage inventors with different expertise profiles. Lettl et al. (2009, p. 244), for example, found that independent and corporate inventors benefit from their expertise differently. They argued that independent inventors are less likely than corporate inventors to be able to bridge diverse technological fields because "they lack the corporate intelligence systems and organizational resources to cope with the corresponding information overload and complexity". They highlight that an organizational setting provides complementary resources that would help the corporate inventors to deal with the negative aspects of and reap the benefits of diverse knowledge. We thus conduct our study of individual inventors within a single company, as a case study of an organization with significant emphasis and investment in R&D, to examine how inventors with different expertise profiles bring value to the organization.

By focusing on inventors within a single firm, we are also able to expand the definition and conceptualization of "value" that inventors bring to firm, by considering not only outcomes that can be determined by publicly available patent data, but also outcomes that are more reflective of the commercial value that inventors actually bring to the firm with their inventions. Prior research used patent data to examine the impact of inventions, usually using forward citations to provide an indication of the value and usefulness of an invention (e.g., Fleming et al., 2007; Nerkar and Paruchuri, 2005). However, other researchers have pointed out that patent citations, while providing a proxy measure that has some correlation with the value of patents (Trajtenberg, 1990), is a rather noisy indicator for the economic value of a patent (Harhoff et al., 1999; Sampat and Ziedonis, 2005). While forward citations provide a good assessment of how the invention influences future research in a domain (Carpenter et al., 1981), they do not capture the extent to which the invention has had a practical impact, e.g., by changing actual products. Little research, so far, has made an explicit link between patent citations and the social and private value of patents (Sampat and Ziedonis, 2005).

We thus argue that while a patent with higher forward citations shows a higher level of technical advancement and signifies a greater influence on a technical domain, it is indicative of the value of the invention rather than its innovative value. The process of innovation is defined as the "development and implementation of new ideas by people" (Van de Ven, 1986, p. 590). In other words, there are two parts to innovation: (1) generating an idea or invention, and (2) converting that invention into a useful application that is implemented and used by others (Roberts, 2007). An invention is a new idea, which may be a recombination of old ideas; it may or may not have economic value. Ideas and inventions have to be moved into a usable form to qualify as an innovation (King et al., 1994; Taylor and Greve, 2006), and this process involves the conversion of an invention into a product, to bring about eventual broad-based utilization of the idea and reap sales for an organization in the process. Both invention and innovation are critical for successful generation of ideas and commercialization of those ideas for development of new products and processes.

Hence, while an inventor's forward citations provide a good indication of the technical value of an inventor's *inventions*, they do not indicate the value that an inventor's *innovations* bring to an organization. The latter is hard to gauge, as it requires the tracking of sales that an inventor's inventions bring for an organization. One way to derive the value that an inventor brings to an organization is to examine the career success of inventors in commercial organizations that have directly tied the career success of inventors to the commercial value they bring to the firm. In our case study organization, R&D personnel are expected to generate inventions that can be used in products that will bring about sales. Thus, the most successful R&D personnel are those who bring the greatest value to the corporation by generating inventions that impact sales and the bottom line (Balkin and Gomez-Mejia, 1984; Kim and Oh, 2002). We define career success as the status of an inventor in the R&D department of the case study organization, which is indicated by whether the inventor has been promoted to the highest technical organizational rank, and whether the inventor has received organizational recognition for the contributions that his/her inventions has brought to the firm. Hence, another key contribution of our research is the broadening of the innovation outcome indicators considered, by examining whether and how individual inventors' expertise breadth and depth influence different innovation outcome indicators.

In order for us to examine our research questions, we adopt a mixed-method approach to empirically develop and test hypotheses about how inventors with different expertise profiles based on their breadth and depth of expertise bring value to the organization. This approach adopts a two-phased design, the first of which involves a qualitative (case study) approach (Eisenhardt, 1989). In this first study, we seek to understand what are the inventors' expertise profiles; how inventors with different expertise profiles approach the innovation process; and what are the environment conditions supporting the development of these expertise profiles. This will provide us with the fundamental understanding of inventors' depth and breadth of expertise and how that influences the way they work. While the prior literature has long established that concepts of breadth and depth are important ways to characterize an individual's expertise, there have been limited field studies that have actually examined how inventors and scientists characterized by deep or broad in their expertise approach the innovation process. We would thus like to first use the qualitative interview study to gain insights into how these different types of inventors may leverage their expertise in different ways and how the organization influences their ability to do so. This understanding will then be integrated with current theoretical concepts from the literature, to generate a set of hypotheses about how inventors with different expertise profiles bring value in different ways to the case study organization. Using patent data, combined with organizational data about individual inventors, we then conduct an empirical test of the hypotheses in a second quantitative study. After discussing the results of the second study, we conclude with implications for future research.

2. Case study site

We conducted a comprehensive study of research scientists in 3M, a diversified technology company known for more than a century for its sustained innovation capabilities. Despite its size (more than 75,000 employees and operations all over the world) and age (established since 1902), 3M has been the poster child of innovation and breakthroughs in R&D and product development. In the practitioner domain, many articles have been written on 3M and its innovation capabilities (e.g., Von Hippel et al., 1999). In the research domain, case studies have showcased best practices adopted by 3M in the areas of IT management (Roepke et al., 2000), human resource management (Angle et al., 1985), and R&D programs evaluation (Krogh et al., 1988). No research to date, however, has systematically examined how individual research scientists work within 3M to generate the innovations and technologies leading to the company's wide range of products. As the R&D department is the starting point for most products and the principal source of innovation within the corporation, this study of research scientists in 3M provides important insights to help us understand how 3M has built and sustained its innovation capabilities for over a century.

3M began by specializing in industrial abrasives and adhesives. Over its 110-year history, it has expanded into a large and diversified organization with more than 60,000 products, with innovation as its key driver for growth. Key 3M products and technologies include adhesives (including cellophane tape and Post-It notes), abrasives, laminates, passive fire protection, dental products, electrical materials, electronic circuits, and optical films. As of 2009, the company was organized into six operating business segments: Industrial and Transportation; Health Care; Safety, Security and Protection Services; Consumer and Office; Display and Graphics; and Electro and Communications.

3M's R&D group includes more than 6500 scientists and engineers. As of 2009, the R&D Group was organized into the corporate research laboratory and the division product development laboratories. The corporate research laboratories focus on basic research in technologies, while the division product development laboratories tend to focus on research more specific to each business segment. While 3M's laboratories are distributed globally, most of the R&D personnel are based in St. Paul, Minnesota, at the heart of the innovation community.

3. Study 1: exploratory study with field interviews

3.1. Method and participants

As we are interested in understanding the role that inventors with different expertise profiles play in helping a company like 3M become and maintain its role as one of the most innovative companies in the world, we first began by conducting one-on-one interviews with 33 research scientists who were sampled based on their expertise profile. To sample interviewees, we first conducted a cluster analysis on their breadth and depth of expertise, based on patent data.[1] Using the FASTCLUS procedure in SAS, we derived a solution that differentiated research scientists into four clusters: (1) high depth and high breadth; (2) high depth and low breadth; (3) low depth and high breadth; and (4) low depth and low breadth. We focused on the first three clusters, as they represented research scientists that had some form of expertise, and we were interested to learn about the approaches that inventors with different expertise profiles adopted toward the invention and innovation process. We randomly sampled interviewees from each cluster, and our interviewees in each cluster included inventors across organizational ranks, and from both the corporate research laboratory and the division product development laboratories.

Following Eisenhardt (1989), the purpose of this phase was to obtain a rich description and understanding of the profile of research scientists and how the breadth and depth of their expertise influenced their approach toward innovation and the ways that they generated and commercialized inventions in 3M. The

[1] Details about the patent data as well as the breadth and depth measures are provided in Section 5 of this paper.

interviews were semi-structured. A set of interview protocol guided the flow of the interviews, but questions were adapted based on interviewees' responses. Each interview lasted for 1–1.5 h. With the permission of the interviewees, interviews were recorded and transcribed. Otherwise, detailed notes were taken and transcribed within the next 24 h. In total, 493 pages of transcribed text with 321,275 words were captured and analyzed.

We began each interview by asking interviewees to describe the domain areas that they have worked in. We then asked them to characterize their own breadth and depth of expertise. We also asked for their views on the advantages and limitations of inventors with breadth or depth of expertise in 3M, and about their experiences of working with such individuals. Interviewees were also asked to describe some recent work projects. During these discussions, interviewees described their approaches toward and views about innovation processes. Finally, we asked for their perceptions about 3M's innovation culture and practices, in order to obtain information about the company's context, culture and organizational practices for innovation. (See Appendix A online for the interview protocol.)

3.2. Data analysis

Our analysis followed an iterative process of moving back and forth between our qualitative data and the literature. We conducted the analysis in two stages.

Stage 1. As a first step in understanding the role of breadth and depth of expertise in an inventor's work, we read the interviews, and used QSR NVivo, a qualitative data analysis program, to code for the following categories: (1) Context and Organizational Culture; (2) Depth and Breadth of Expertise; (3) Strategies adopted by Inventors. We also used open NVivo coding to capture additional themes that surfaced in the data collected.

Stage 2. Based on the initial analysis, we focused on the discussions relating to inventors' expertise. We then classified each inventor into a different expertise profile, and we used the data to answer the following questions: (1) what are the advantages and disadvantages of breadth and depth of expertise for 3M inventors; (2) what are the expertise profiles of inventors in 3M; (3) how do the inventors become who they are (in terms of their expertise profile); (4) how do inventors with different expertise profiles succeed in the organization; and (5) how does 3M provide the environment conditions that are conducive to the development and success of inventors with different expertise profiles? We present the results of this analysis in the subsequent section.

3.3. Results

Breadth and depth of expertise. Interviewees identified the strengths and weaknesses of having broad versus deep expertise for R&D work in 3M (see Table 1, which includes supporting quotes from interviews). According to our interview findings, inventors who have deep expertise are useful for providing detailed and accurate analysis of a problem, and solutions to difficult technical problems in a domain. Their knowledge also gives them the expertise and knowledge to make difficult trade-offs and the ability to predict what will go wrong. These are qualities that put people with deep expertise in good positions to generate important discoveries in their domain of expertise. On the other hand, inventors with broad expertise are usually the ones who are able to relate technologies to new areas as they have the breadth of expertise to know how the varied technical issues may be solved. Inventors with broad expertise are also known to be good for suggesting new perspectives and new ways in looking at a problem. This may be partly because their lack of deep expertise may sometimes be a blessing as they are not overly burdened by existing viewpoints or knowledge of everything that may go wrong. Overall, our interviewees recognized that broad expertise as well as deep expertise are useful in their own ways, and are both required for the innovation process. One quote from our interviewee summed this up well:

> "Let's look at this glass as an example. As I refine this invention, do I want depth or breath? I would argue I need both. I need depth to say, "what is it that this is capable of being?" You can see some issues here on this sample, it is kind of yellowish, maybe a little hazy. The person with depth will recognize the problems here, and work out: what are the ways in which one could solve these problems... There's another question, "what is this good for?" We can really do this high index, really inexpensive glass, what markets would value it? Now this is not a depth question, it's a breadth question."

Table 1
Interview quotes illustrating the usefulness of deep versus broad expertise.

Key finding	Quote
Usefulness of deep expertise	
Provide detailed and accurate analysis	"A depth person [sic] usually would be able to analyze a problem in much more detail and with accuracy and quality that I probably couldn't."
Make discoveries in areas that experts are familiar with	"Those people who are let's just say light on being an expert in any one single area are not likely to make discoveries or fundamental understandings in any one of those areas, any discipline. But... since I work in microreplication for 26 years, I am likely to be able to generate some good discoveries in the microrep domain, as I have an understanding of what we can do, and what we can't do."
Make trade-offs	"So you got the ability to understand how to make some tradeoffs. For example, if 2 things might have similar optical performance while one of them is easier to manufacture, you have the depth to understand that."
Usefulness of broad expertise	
Suggest new ways of looking at things	I'll pose something to him [a person with broad expertise], and he always surprises me by coming up with some way of looking at it that I never would have thought of.
Able to understand how technologies can relate to other areas	If you say to me "we need some discoveries in resin chemistry to put this microreplication in a UV environment or a chemical environment or whatever", you need a person with broad expertise to do that.
Not burdened by prior knowledge	If you know all the things that can possibly go wrong... that makes us a little scared to experiment and try new things

3.4. Expertise profiles of 3M inventors

Our interviews revealed that there are specialists, with deep and narrow expertise, and generalists, with broad and shallow expertise, amongst the 3M inventors that we interviewed, and they approached the innovation process very differently. Interestingly, we found a third group of inventors, who exhibited an expertise profile that had both deep and broad expertise. We discuss each of the three groups of inventors, how they developed their expertise profile, how they leveraged their expertise profile to become successful in 3M, and what characteristics of the 3M environment helped them.

3.5. Specialists

R&D personnel are typically recognized to be specialists, as they spend many years working on a domain, and are highly knowledgeable about the domain. Hence, it was no surprise to find inventors with such an expertise profile in 3M. Many of the specialists we spoke with explained that to become and stay as specialists, they required focus and perseverance. An eleven year project described below by an interviewee testified to the requirement of such focus and perseverance.

> "D3 [pseudonym] technology was the most difficult. . . For the first 7 years, it was sort of a 15% skunk work kind of thing done in a lab without a lot of business pull, which was probably. . . sort of a typical 3M story. It was a good thing it probably didn't have more pull because we didn't know how to do it. So we knew what we wanted to make but we didn't know how to make it. So we kind of went through a number of iterations, learning each step of the way before we finally sorted out and about in 2001, it became apparent that this actually was possible. . . That was really a gruelling experience but also a fantastic one. . ."

The specialists we interviewed exhibited such determination to work persistently on a particular technology in order to achieve a significant breakthrough in the invention. As highlighted by one interviewee, a specialist is typically someone who is "willing to be bashing up this technology again and again and again and really shape it out in depth".

3.6. Strategies adopted by specialists to become successful in 3M

a. Fit niche requirements of firms. The interviews revealed that some areas of expertise were in greater demand in 3M given the businesses that the company was in. For example, many materials sold by 3M, like diaper tapes and tape backings are non-woven materials, which are classified as polyolefins. Hence, as noted by one interviewee: "Having expertise in [polyolefin] is particularly advantageous here [in 3M]". Not everyone's training, however, was in the specific niche areas that 3M dealt with. Hence, several interviewees highlighted that individuals sometimes needed to actively identify the right niche areas of expertise required by the firm, and cultivate their expertise in that area, early on in their careers and become specialists in these new areas of expertise. As highlighted by one interviewee:

> "After joining 3M, I realized that there were many people. . .too many people working in the fluorochemicals. So you have to find your own niche, so I started working in fluoropolymers instead of fluorochemicals. So I guess I was a small molecular chemist, understanding reaction mechanisms of small molecules. I never deal with polymers – that was a big change for me. However I feel that that was the company's need. You got to do something that is interesting in the company, provide some value to the company."

b. Avoid tunnel vision by stepping back to fundamental principles. While the ability of specialists to focus is a key trait enabling them to work through problems for generating inventions, being too focused, however, may not always be positive. It becomes critical, therefore, for specialists to recognize their tendency to become too narrowly focused, and to consciously take a step back and analyze the issue based on fundamental principles. By returning to the fundamentals, specialists maintain their focus while not falling into the trap of becoming tunnel-visioned.

> "You make invested advances by, in my opinion, failing often and having to sit down and think about what is really controlling this?. . . It's all categorization and you gotta put it in boxes so that you can figure out what the end relationships are and if you can get to that point then you can be successful in manipulating it. And if you're not and you just sit there, you'll never get out of the box. It's like you're down in a cave with no ladder, you can't climb out. You just feel that you're gonna get buried. But you gotta get to know the physical property of this. What is the true physics or chemistry that's controlling what you're doing and when you start thinking about that, then it's pretty easy to stay focused and make really big inventions."

Environment conditions conducive to specialists. Our interview results reveal several organizational practices that had been particularly useful for specialists to be able to contribute to the organization. As specialists are characterized by their perseverance and focus, they may work on a technology for years before they may be able to show progress, but their inventions have the potential to create completely new technologies for the firm. This has several implications for the organization. First, the specialists need to be given the space to experiment and the firm needs to tolerate failures that will result from the experimentation. In 3M, the practice of allowing inventors to work on side projects for 15% of their time provides inventors with the freedom to experiment, and the innovation grants provided by the firm also provides additional funds for inventors to sustain the initial and most risky phase of their exploratory R&D work. In general, slack and less pressure to show results in the short term are all key environmental characteristics that helped specialists to develop highly impactful technologies, as highlighted by the following interviewee:

> "We made a ton of money during those years on some product protected by patents, made it a little easier for us to invent basic technology, might be tougher to do that now. On the other hand, the history of 3M shows that you will be able to try to find some ways to keep things going at low levels before they get successful."

In addition, perseverance was required not only on the part of the individual inventor, but also on the part of the management, in order to continue to support investment into technologies that have the potential, but may have failed in the short term. As highlighted by one interviewee:

> "Our first couple of projects were not successful, we were technically successful but for various business reasons we could not reach the finish line, but management at 3M was kind enough to continue. They had the foresight to see the value of the technology and significant investment was made at that time to strategically value the technology."

3.7. Generalists

Generalists were inventors with expertise in a broad range of domain areas, but without deep expertise in any one of them. Our interviews show that the typical generalist inventor had broad interests and can become easily bored if s/he stays for too long in one domain area. The generalist is characterized as someone who prefers to work in new areas constantly. One generalist interviewee explained his preference for working in diverse areas:

> "I would always have 4 or 5 projects I was working on and I would purposefully try to make them diverse across the entire company. . . I wouldn't just focus in on our medical group or our Display and Graphics group or something. I would say: "I am working on 2 things with them, let's see if I can go talk with some friends that I know in a different complete group or division just to say: "Let's have lunch and what are you working on? What kind of things might I be able to help with or what are you looking at for the future?""

We found that generalists often broadened their expertise in one of two ways. First, they were willing to constantly learn about completely new domain areas. One interviewee, for example, highlighted that he had to learn several new technological areas in his 10 years with 3M: "film manufacturing, coating processes, anti-static materials, hardcoats, UV curable materials – Things that I had very little to do with in my previous life". Another interviewee went to the extent of taking courses in a University to learn about the medical domain in order to better understand the area:

> "So when I came to medical [division], I obviously wasn't trained in medical at all, I'm an engineer. The first thing I found out, I didn't know anything about medical, so I went back to University and took nano-physiology and all these things to get up to speed on body parts and stuff. That's the key. In this company, you can bounce. you may bounce around to totally different areas that you're not used to. You just fortify your base knowledge and learn more about that particular area that you're in."

Second, interviewees also leveraged their previous knowledge by creatively generating new combinations that integrated components of their prior knowledge and new domain areas that they had to learn about. One interviewee explained:

> "I combine [the new domain area – a thermoplastic compound] with some of the knowledge that I had [a thermosetting compound] and I came up with something that is totally different, which is a combination of 2 polymers... So combining both, people used to say, "how can you mix these 2 polymers that are totally incompatible, they don't like each other?" My answer is that, "why should you automatically limit yourself?" You have to do it and see what you get out of that. And actually, the incompatibility is an advantage, because when we mix the 2 components together, one of the components, a thermoset, which is in a minor face actually migrates towards the interface, when you are trying to bond this material. So you form a structural bond with very little thermoset, so the thermoplastic face is just carrying the thermoset. So the combination of those 2 things, turned out to generate a very useful invention."

3.8. Strategies adopted by generalists to become successful in 3M

Generalists adopted a very different approach toward innovation compared to specialists. We discuss two key strategies adopted by generalists, which reveal that while generalists may work in diverse domains, their approach toward innovation is similar across domains:

a. Focus on application. In contrast to specialists who are focused more on the development of groundbreaking technologies, generalists appear to emphasize the application of technologies into useful products, and the integration of multiple technologies into a product. As highlighted by one interviewee,

> "I belong to the class of people who... apply utility to [the technology]. For example, tapes is nothing more than a sticky mess, unless you have a good way of dispensing it, unless this little roll that it is on freely rotates and you can access it, cut it and it still stays in part. We are the system integrators."

b. Focus on fundamental skills. Our interviewees also highlighted that despite changing domains, and working in new domains, they distil a set of fundamental skills that they take with them and apply, regardless of the domain area. First and foremost, interviewees highlighted the importance of problem solving skills, which they have cultivated and honed, as they worked across domains:

> "I think you learn at 3M, it is not necessarily what you know, but it is your problem-solving skills that are most important. You'll see people change fields fairly dramatically, but the problem-solving skills remain applicable no matter your domain."

Other skills that are portable across domains include the ability to observe and understand customer needs, and to conduct competitive analysis. As highlighted by one interviewee:

> "No matter where I go, the key is to really understand the customer and to create, looking at the scene, how they're doing this. I observe customers all the time and what I think they're doing wrong, what I think they can do better... that's how I create ideas off them."

Environment conditions conducive to generalists. 3M has an environment that makes it particularly conducive to generalists. 3M has more than 60,000 products in six operating business segments. The firm has a "periodic table of technologies", which lists 45 different technologies that the company owns, ranging from abrasives to biotechnology, highlighting the breadth of technologies that the company deals with. Interviewees point out that one key attraction of working in 3M is that the company has many technologies and talent knowledgeable about them under one roof. This, coupled with having a very open and helping culture, helps individuals to obtain access to significant resources.

> "We have more technologies under one roof here at 3M than almost anybody else in the world and it is freely accessible... I've told people for a long time I'm a kid in a candy store here. I still feel like a kid you know, I enjoy going to the annual events and seeing the new technologies and figuring out is there something I can do to help them or is there some way they can help me in my projects."

The diversity of the firm, coupled with the 3M policy – a philosophy widely-accepted by employees – that the technology is owned by the company, prevents people from having "Not-Invented-Here" syndromes, and encourages individuals to explore innovative associations between different technologies.

> "One of the biggest advantages that we have is – we believe in 3M, the product belongs to the different businesses but the technology belongs to the company. People – at least the technical community really truly believe that and it is supported by the top most management. That's what enables the barrierless movement of technology. If you look at our "periodic table of technologies", we can pull from all these different areas to put something together. That's what we just take for granted."

Hence, the diversity of the firm and the opportunity to access and combine many different technologies provides a conducive environment for generalists to flourish.

3.9. Polymaths

Prior research tends to classify individuals into specialists (individuals with high depth and low breadth of expertise) or generalists (individuals with high breadth and low depth of expertise). Among the 3M inventors, we found a group of people who could be considered polymaths – individuals with both high depth and high breadth of expertise. These polymath inventors are recognized experts with deep expertise in one or more core domain areas, but they have widened their knowledge and expertise to apply the technologies that they have championed widely across the organization. The following quote appropriately characterizes a polymath inventor:

> "If you wanna try to achieve, then you pretty much have to be very focused in one area. I think each one of those individuals [corporate scientists] probably has one area that they probably are considered one of the top people in the field, but at the same time, they also recognize that if you really want to maximize, maybe that particular area, you really need the breadth

of learning in other areas, and it is hard, you can't be the best at everything, I think a lot of us try to find an area where we try to be one of the best and then maybe we can continue to learn other areas."

This finding highlights that the polymath inventors were not deep in all the areas that they were knowledgeable about; rather, they had deep expertise in their core domain area, and they learn about new technological domains as they apply and relate their core expertise to new areas, thus gaining some knowledge of a broad range of domain areas.

In addition, rather than simply applying technologies broadly to new domains, the deep knowledge that the polymath inventors have about their core domains of expertise allow them to effectively recombine and integrate technologies from their core domain areas to new domain areas. This process of recombination and integration does not simply generate applications to existing technologies, but rather, generates new inventions that can be applied to multiple products. An interviewee provided a good example illustrating this point:

> "My core domain expertise is in fluorochemicals. I've integrated my domain with the electrical domain to create the electrical fluorination process to make fluorochemicals... and that electrical fluorination process produces some reactive molecules that we've been able to take and convert to new materials that 3M hadn't had available before and those materials have unique properties that have uses in industry, so we've been able to develop products from them that didn't exist previously."

3.10. *Strategies adopted by polymaths to become successful in 3M*

Polymaths adopt strategies that leverage both their breadth and depth of expertise.

a. Evaluation and identification of ideas. Polymath inventors use both their breadth and depth to actively evaluate ideas and identify the ones worthwhile to pursue. One polymath inventor, for example, explains his thought process when evaluating ideas:

> "One of the things I do a great deal is map inventions. I look at the initial invention and distill it down to what's different, what is it that this invention does that previous inventions or technologies could not? So, I look at this [picks up a piece of glass], number one by far, it is cheap and inexpensive to form and has really high index. So these are the two differentiators, and so we start asking the question, what groups would care? What industries would care about this and value it? And we'll come up with a list... could be biomedical, automotive, commercial graphics, or lighting. And I always go through those and say, ok then which one of this would REALLY like this."

The quote shows that his depth of expertise plays a key role in identifying the technical contributions of an idea, while he draws upon his breadth of expertise to evaluate the potential ways the invention can impact different industries.

b. Championing technologies in core domain. Polymath inventors adopt a strategy of actively championing one or more technologies in their core domain, applying, integrating and recombining this technology with a broad spectrum of domains and technologies. As pointed out by a polymath inventor, they would be "living, breathing, eating and sleeping [the technology], with a singular focus on getting this thing to be successful". The polymath's approach of championing a technology typically involves developing the technology and obtaining broad usage for the technology. This was no easy feat, as illustrated by the experiences of one polymath. He described how his first project failed due to a business decision not to continue investing in his technology, but instead of giving up, he decided to pursue a broad strategy of championing the technology.

> "When that project was a failure and I came back to St Paul, at that time, I had the opportunity to think – what could I do at that time. So that's when I started thinking that this technology should be looked at more broadly than just diamond-like carbon films, because the technology is broadly applicable... the focus was not a good thing. When I branched out into all the other areas that the technology could be applied to, that was when I found several new products."

This polymath inventor, however, faced multiple hurdles in trying to apply his technology broadly to new areas; it was his breadth and depth of expertise that enabled him to work through the problems. As the technology he championed was new, it made the manufacturing division skeptical about the feasibility of the technology in scaling up for production. In order to "sell" the technology to the division, he engineered the machines to create prototypes showing the ability to scale and provided cost estimates about how he could help the business unit to save money. It was not typical of scientists to have to build the actual machines to manufacture using their technology, but his depth of expertise enabled him to do so. His breadth of expertise enabled him to understand the manufacturing requirements and costs of different business units, thus enabling him to gain wide acceptance for the new technology.

While polymath and generalist inventors both focus on applications and recombinations of technologies, the difference between them is that the polymath inventors anchor themselves in their core domain technologies, and they consistently try to apply and integrate these technologies to new areas. Generalist inventors, on the other hand, focus on applications and recombinations of different sets of technologies across time. The benefits of repeatedly applying and making recombinations involving the technologies in the core domain are twofold. First, polymath inventors find that they not only learn about new technological domains, but they also gain a greater understanding of their own core technologies. Second, the disciplined practice of repeatedly applying and integrating the same technologies with new ones result in experience, which makes it easier for the polymath inventors to make new applications, even though the process may not be a simple one. As highlighted by a polymath inventor:

> "When you wanna make false shots, you're not gonna do it by going to eat ice-cream. You're gonna go out and shoot 300 false shots everyday. And I bet you if you do that for 5 years, you're gonna get a whole lot better than you did when you first started and you gotta keep asking those same questions and a lot of times, what always marvels me is how we assume that discussions happen at a corporation at 3M and we just jump in and take all our resources and start flying. Did we really know what we're going after, did we really? Is this really the best way we can do that? Where else could we get resources from? What others areas would have interest in these type of things?"

Environment conditions conducive to polymaths. Polymath inventors, through the process of developing and working with the technologies in their core domain, and applying the technology to new domain areas, often develop deep passion for their technologies, and strong beliefs about the potential of the technology to bring value in different domains. This provides strong motivation for the polymath inventors to continue their course of championing their technologies and applying them widely. In terms of the organizational environment, 3M has publicly stated that 25 percent of its sales must be generated from products that did not exist five years ago (Kunkel, 1997). The company also places significant emphasis on evaluating inventors' contributions based on the commercial value that their inventions have generated. Hence, with 3M's strong emphasis on R&D's need to contribute to product sales, this provides even more impetus for the polymath inventor to ensure they are able to integrate and apply their technologies to generate commercial value to the organization.

4. Theory and hypotheses

Next, we discuss how the insights and findings from the qualitative study integrate with the concepts and theory from existing literature, generating a set of theoretical hypotheses that we later test in a separate quantitative study. This will allow us to make conclusions that are supported by theory, about how 3M leverages inventors with different expertise profiles to bring value to the organization.

The interview findings from the qualitative study revealed that individuals often depended on creative recombinations of their existing knowledge to generate new inventions. This is consistent with Schumpeter (1934)'s view that innovation is the recombination of existing resources, in the form of existing ideas, materials and forces. We thus draw on this literature, and we also integrate the findings and insights from the qualitative interviews with the psychology of science literature, which discuss the role of individual cognition in facilitating the generation of novel ideas by individuals (Weisberg, 1999), in order to create insights into the individual psychological processes leading to scientific creativity (Feist and Gorman, 1998; Klahr and Simon, 1999).

4.1. Dimensions of individuals' expertise: breadth and depth

Prior research tends to conceptualize depth and breadth of individual expertise as two ends of the same dimension, due to the trade-offs required in investing the time to cultivate either specialized areas of expertise, or a broad range of expertise domains (Kim, 1989; Schilling et al., 2003). As noted by Jones (2008), "given an investment in time, one might become a generalist with modest knowledge about multiple tasks or a specialist with deep knowledge at a particular task".

At the organizational level of analysis, however, Katila and Ahuja (2002) conceptualized the breadth and depth of a firm's knowledge as the scope (local versus distant) of the firm's search efforts and the degree to which existing knowledge is exploited or reused respectively. This conceptualization effectively treats the breadth and depth of a firm's knowledge as two separate dimensions rather than two ends of the same dimension. The idea that organizations can effectively achieve both breadth and depth of knowledge is consistent with the finding that organizations often have loosely coupled and differentiated subunits or individuals, each specializing in either knowledge search and exploration or knowledge reuse and exploitation (Gupta et al., 2006).

Our qualitative study shows that even at the individual level, one can consider breadth and depth of inventor expertise as two separate dimensions, rather than two ends of the same dimension, as we found that there are a group of polymath 3M inventors who have both high breadth and high depth of expertise. These inventors are not "jack of all trades and master of all trades"; rather, the individuals have some knowledge of many technical domain areas, but deep expertise in only one or a few core technical domain areas. Effectively, these inventors have "T-shaped skills" – skills that are both deep (represented by the vertical part of the "T") and broad (represented by the horizontal part of the "T") (Iansiti, 1993; Madhavan and Grover, 1998).

Our interviews show that the core expertise areas form the heart of and foundation for the individual to apply his or her core expertise to new domains. These inventors often passionately champion the technologies they invent in their core domain areas, and widely apply and integrate the technologies in different domains, and at the same time, learn about new domain areas. Prior studies in cognitive psychology have established the associative nature of knowledge – individuals comprehend and encode new knowledge into memory by linking it to pre-existing knowledge components (Ellis, 1965; Ericsson and Lehmann, 1996). Hence, as shown in our interviews, individuals build both breadth and depth of expertise by anchoring themselves in one or a few core technical domain areas, and understanding how their core domain expertise area interacts with other disciplines. Thus individuals learn to recombine existing components in novel ways while simultaneously building up new connections and new cognitive nodes of knowledge. Once an individual builds up a rich repertoire of knowledge components and also constructs a dense scaffolding of strengthened links between existing knowledge components and new knowledge components, he or she can more easily integrate new knowledge components into a large web of existing knowledge components (Schilling et al., 2003).

		Breadth of Expertise	
		Low	**High**
Depth of Expertise	**Low**	Novice	Generalist
	High	Specialist	Polymath

Fig. 1. Expertise profiles of individuals.

Fig. 1 shows how the two dimensions of depth and breadth of individual expertise interact to generate different archetypes of expertise profiles. In the next section, we hypothesize about how individuals with different expertise profiles will bring value to an organization.

4.2. Hypotheses

Depth of expertise. Our interview study reveals how specialists tend to approach the innovation process. First, the deep expertise of specialists implies that they are excellent problem solvers, able to provide high quality and detailed analysis of problems and solutions. This is consistent with psychological research that has found that people who are considered experts in a domain solve problems better and faster than non-experts (Ericsson and Lehmann, 1996). Our interview findings also revealed that deep knowledge allows specialists to be able to understand the fundamental principles driving a particular domain or problem. The ability to understand fundamental components and the relationships between them enables specialists to effectively make recombinations of existing components. Experiences gained experimenting with combinations of different components teach them about the properties of each component and enable them to make educated guesses about potential outcomes and problems when they make new combinations of the familiar components or use a component in a new context. This enables individuals with greater depth of knowledge to navigate a landscape with tightly coupled components and to invent new recombinations that would have significant impact on a technical field (Fleming, 2001).

Prior research has also shown that individuals with greater depth of expertise are better able to make relevant inferences about principles and abstractions that are not obvious from the surface presentation of the problem (Chi et al., 1988). The ability to go beyond the surface presentation of a problem, to identify the underlying principles and assumptions, and to infer further related knowledge is critical to advancing fundamental knowledge that can create significant technical impact. The ability to recognize patterns at an abstracted level enables people with deep expertise to generate a coherent, complete and principled representation of a domain area (Chi et al., 1989). These experts can make use of systematic solutions and analogical reasoning (Holyoak and Thagard, 1997) to solve novel problems, as opposed to depending completely on trial and error (Mumford, 2000).

Hence, the inherent advantages afforded by deep expertise, coupled with the tendency for specialists to focus and persevere in the face of difficulties, solving problems associated with a technology, increase the likelihood that specialists can generate highly impactful technological inventions that would have significant influence in the technical domain. Hence, we hypothesize:

H1. Individuals with greater depth of expertise in their core area of expertise are more likely to be able to generate technically influential inventions.

Breadth of expertise. The findings of the interview study shows that generalists leverage their breadth of knowledge by applying and recombining their expertise in creative ways. This is in line with arguments from prior research. Simonton (2003), for example, notes that a larger number of cognitive elements available for association and the breadth of these elements increase the probability of finding novel combinations amongst these elements. Research on creativity also highlights that divergent-thinking, or the extent to which individuals are able to generate a wide variety of ideas, is critical for creativity (Baer, 1993). Both Greve and Taylor (2000) and Katila and Ahuja (2002) found that expanding the scope of search increases idea variety, creating more ways of combining knowledge that challenge the assumptions and beliefs constraining innovation. Increasing the number of cognitive elements increases the number of options available to inventors for solving novel problems. These arguments highlight that breadth of expertise increase the tendency to generate a higher number of ideas.

Our interview findings show that while the focus on applications and recombinations of generalists are similar to the polymath inventors, the difference is their focus on generating many different recombinations of different technologies, rather than recombinations involving the same technologies that polymath inventors are anchored in. This equips them with the ability to generate multiple ideas and inventions, although not necessarily the most impactful or useful ones. This is because while breadth of knowledge enables individuals to recombine disparate knowledge components, thus generating many novel ideas, it does not necessarily equip them to select the most appropriate combinations that can generate the most influential or commercially worthwhile ideas. As noted by Poincaré (1921, p. 386), the key to invention is not in making a large number of "useless combinations" but "in making those which are useful and which are only a small minority". Hence, we hypothesize:

H2. Individuals with greater breadth of expertise in many domain areas are more likely to be able to generate more inventions.

Breadth and depth of expertise. While individuals with deep expertise are likely to generate technically influential inventions, and those with broad expertise are well-positioned to generate many inventions, we argue that an inventor needs both breadth and depth of expertise to have a successful career of innovating products that generate revenue for the firm. Inventors with successful careers create value for their organizations not only by generating technical inventions, but also by applying the inventions to one or more market needs and transforming the technical inventions into useful products. Hence, it is not sufficient for an inventor to come up with a novel idea and patent it; that novel idea must be converted into a real, commercially successful product. We argue that the key to an innovator's career success is the ability to structure the transition from a novel idea to a successful product. To make this transition, one needs to be able to recognize when a novel idea has the potential to become a saleable product. More importantly, inventors bring value to their organization by transitioning a novel idea into a series of related products that can build upon each other and have broad impact on an organization's sales revenue.

Our interview findings reveal that the polymath inventor draws on both his breadth and depth of expertise to help evaluate ideas and identify the most fruitful ideas to work with, and both dimensions of expertise help him to identify novel ideas that have the potential to bring commercial value to the firm. In addition, through active championing of technologies in his/her core domain area, the polymath inventor plays a key role in transitioning a novel idea or invention into products that provide commercial value to the firm. Both depth and breadth of knowledge are critical to help the polymath inventor through this process. First, depth of knowledge is critical for inventors to anticipate and solve problems that arise from integrating disparate areas and knowledge components, as technological challenges increase proportionately with the amount of knowledge components to be integrated (Katila and Ahuja, 2002). Moreover, the innovation process is often uncertain and risky (Kline and Rosenberg, 1986). An innovator often has to make hypotheses and assumptions about which technological constraints can be overcome (sometimes in the face of ridicule from other established scientists) to arrive at a breakthrough innovation. An individual needs deep expertise in order to have the audacity and confidence to challenge well accepted assumptions and constraints and to invest time and resources in doing so.

On the other hand, depth of expertise also has its downside. Individuals with deep but narrow expertise tend to pursue a single technological trajectory, unable to adopt ideas and incorporate innovation from other fields. When individuals become too focused on examining only a few technological components, their innovation potential may be limited by the finite and restricted set of connections they can derive from the small set of knowledge components. Depth of expertise and experience also make experts very aware of technological constraints, so much so that inventors may sometimes forget that some constraints are only assumptions and may be tested with new technological advances. However, as individuals gain breadth of knowledge, they learn how their core expertise domain interacts with other components (Madhavan and Grover, 1998), thus enabling them to not only learn about new domain areas, but also learn new properties about their own core area of expertise. Widening perspective enables innovators to constantly question existing assumptions and generate different ways of looking at a problem and prevents self-imposed biases and stereotypes about ways that they and others conduct their work (Bunderson and Sutcliffe, 2002).

Hence, individuals with both breadth and depth of expertise can utilize their specialized knowledge and deep understanding of a specific area and their broad exposure to new ideas and new variations to generate unique combinations of a broad array of components and work through the problems of integrating the disparate components (Yayavaram and Ahuja, 2008). This combination of expertise breadth and depth allows them to generate technical inventions and also apply the inventions broadly in new market areas, thus generating value for their corporation. We thus hypothesize:

H3. Individuals with greater depth of expertise in their core expertise areas and breadth of expertise in many domain areas are more likely to be successful in their careers with 3M.

5. Study 2: test of hypotheses

To test our hypotheses, which were derived based on insights from the interviews and the literature, we conducted a quantitative study that provided a test of the hypotheses, by using a combination of data sources. First, as 3M places significant emphasis on intellectual property protection, its research scientists file patents extensively to protect their inventions. The patent data served as a good source of information for inventors' expertise and the impact they have on their technical domains. We supplemented the patent data with organizational data about individual inventors, such as their division, their organizational rank and whether they had received the Carlton Award, variables that provide key information about the inventors' career success in 3M. The archival data from different sources allowed us to test our hypotheses quantitatively.

Patent data. Raw patent data for the analysis was obtained from the Delphion database; it included a total of 11,411 U.S. utility patents that were granted to 3M, as of December 2006. The patent application dates ranged from 1976 to 2006. A utility patent is one that protects a "new and useful process, machine, manufacture, or composition of matter" (USPTO, 2009). Almost all US patents are utility patents, and most social science research using patent data includes only utility patents (Fleming et al., 2007). As there is no unique identifier for each inventor in the patent database, we adapted Singh (2005)'s algorithm (2005) to identify when two patent records refer to the same inventor. We regard two inventors to be the same if and only if all of the following conditions hold: (1) there was an exact match for the first and last names; (2) the middle initials, if available, were the same; and (3) when the middle initial field was blank, the records also overlapped on at least 1 of the 3-digit U.S. Patent Classification (UPC) code. We also checked the data against the organizational workforce directory where applicable, identifying individuals with duplicate names and their respective domain areas.

In the following sections, we first explain the measures used for breadth and depth of inventors' expertise. We then explain the analyses conducted and measures used for each analytic set.

5.1. Measures of inventors' expertise

We used patent data to obtain measures of the breadth and depth of inventors' expertise. The U.S. Patent Office organizes all technology into approximately 400 classes and 100,000 subclasses; each class is known as the U.S. Patent Classification (UPC). Each patent is assigned to one or more UPC (Fleming et al., 2007). Each UPC therefore represents a technological area that an inventor works in. Based on the UPC assignments to the patents published by each individual, we worked out the breadth and depth of expertise for each inventor.[2] The patent office requires that patented ideas be novel, unobvious, and useful. Our research assumes that if an inventor has repeatedly created inventive patent claims in specific subject areas, the inventor has likely achieved a level of expertise in the field. The expertise may be in advancing the field, in developing new combinations leveraging at least one area of expertise, or both.

Breadth of expertise. Adopting the same measure used by Fleming et al. (2007), we measured an inventor's breadth of experience as the number of unique UPC codes assigned to the inventor's patents.[3] Prior literature has used the Herfindahl index (HI)[4] or adapted versions of the HI, which measures the extent to which an inventor's patents are concentrated in one UPC, or equally distributed across all the UPCs, to measure the technological diversity of firms or patents (Gruber et al., 2012; Lahiri, 2010). This measure, however, is effectively a measure of both the breadth and depth of a person's expertise. A person who has deep expertise would have a high HI (close to one), whereas a person who has broad expertise would have a low HI (close to 1/N). Indeed, with the exception of Gruber et al. (2012), most studies that have used this measure have only examined the diversity of a firm's knowledge or patent, but not examined the depth of a firm's knowledge or patents.

Depth of expertise. As our conceptualization of depth of expertise is about inventors' expertise in their core domain areas, we first identified the inventor's core domain area, which is defined as the UPC code in which the inventor publishes most frequently.[5] We then calculated the inventor's depth of expertise as the total number of patents the focal inventor has published in his or her core area of expertise, divided by the inventor's total number of patents. This measure is adapted from the measure of concentration ratio, and it effectively measures the share of patents published by a focal inventor that is classified in the UPC code in which the focal inventor publishes most frequently. We conducted further sensitivity analysis to examine how the results would change when we defined one's core areas of expertise as the two or three UPC codes in which an inventor publishes most frequently,[6] and the results remain unchanged.

Face validity checks on expertise measures. We used the interviews described in Study 1 to help verify the face validity of our expertise measures. Based on the interviewees' descriptions of their areas of expertise and their characterizations of the breadth and depth of their expertise, the first author coded each interviewee as a specialist, generalist or polymath inventor. A second independent rater coded the same set of interviews. The interrater agreement was 87.9. There was disagreement in only two cases; those disagreements were resolved by discussion between the two raters. We then compared the classification of the interviewees based on the coding of the interviews to the classification

[2] Prior literature has also used the UPCs of the forward citations of a patent to measure the diversity of a patent (Henderson and Cockburn, 1994; Jaffe et al., 1993), but doing so effectively measures the influence of a patent, rather than the breadth of the patent and hence the breadth of the inventor. On the other hand, prior literature has also used the technological classifications of the backward citations of patents or their search reports to calculate the diversity and depth of patents (Gruber et al., 2012). We chose to use the technological classifications of the patents generated by inventors to calculate the breadth measures as we felt that a patent is more accurately classified with its own technological class. UPC classifications are accorded to patents based on the claims stated within the application document, one of the most important parts of the patent document. Hence, the UPCs are generally more precise in describing the technological classes a patent belongs to, compared to the technological classes of the backward citations of a patent or its search report. As we are measuring the breadth and depth of inventors expertise, we require the technological classes to describe the patent as precisely as possible, whereas prior research that have used backward citations was calculating the breadth of technological recombinations achieved by a patent, and this was used as an outcome variable to indicate the extent to which an inventor has been successful in combining different technologies.

[3] One might also suggest that the number of technological classes (our current breadth measure) should be scaled by the number of patents, as breadth is easier to produce for scientists with more patents. As the distribution of number of patents is highly skewed, we scale the breadth measure with the log number of patents, which is consistent with the inclusion of the log number of patents as a control variable. Using this normalized breadth measure provides consistent results with the results presented in the paper.

[4] Herfindahl index is measured by $H = \sum_{i=1}^{n} S_1^2$, where S_i is the proportion of an inventor's patents in UPC i, and n is the total number of UPCs that the inventor has worked in.

[5] We conducted sensitivity analysis by using an alternative method of defining one's core expertise. In our current definition, we restricted core expertise to be in predefined numbers of areas. But different people could potentially have different numbers of core expertise. In this analysis, we define core expertise to be the UPCs in which individuals have published at least 50% of their patents, or UPCs in which individuals have published at least 10 patents. Defining core expertise as the UPCs in which individuals have published at least a certain percentage of their patents caters for individuals who may not have many patents. Defining core expertise as UPCs in which individuals have published at least 10 patents caters for individuals who may have many patents. This analysis presents similar results as those presented in the paper.

[6] This is to cater for the possibility that an individual may have more than one area of core expertise.

Table 2
Descriptive statistics of clusters and interviewees.

	No. of inventors	Depth of expertise	Breadth of expertise
Specialists	7	89.33	8.43
Generalists	9	20.22	24.33
Polymaths	17	78.77	30.47

of the inventors based on the patent data. There was agreement in the classifications in all but three cases, providing an inter-rater agreement of 81.8. Thus, there is reasonably strong evidence that the measures used to calculate the breadth and depth of expertise from the patent data were good indicators of the expertise of individuals. Table 2 shows the expertise profile of the interviewees.

5.2. Dependent variables and levels of analysis

We conducted three sets of analyses at three distinct levels of analysis, with different dependent variables. In line with prior research using patent data (Fleming et al., 2007; Hall et al., 2002), all variables were calculated by patent application date (or publication date).

Analysis 1. The first set of analysis tests hypothesis 1 by examining how the breadth and depth of expertise of the inventors of a patent affected the forward citations of the patent. The dependent variable for this analysis is the number of forward citations per patent as of 2007 (#Forward Cites). Forward citations are commonly used as proxies for the technical impact of a patent (Hall et al., 2001). A patent with higher forward citations shows a higher level of technical advancement and signifies a greater impact and influence on a technical domain (Carpenter et al., 1981). The independent variables are the average breadth and average depth of the inventors of the focal patent, based on the patents published by the inventors prior to the filing of the focal patent. As controls, we included variables that have been included in similar analysis of patent forward citations by Fleming and Sorenson (2001) and Fleming (2001). Table 3 provides a description of the control variables included in the analysis, and Table 4 shows the descriptive statistics and correlations of the variables included in the analysis.

As the dependent variable takes on integer values, researchers typically make use of Poisson models to analyze such count data. Adopting a similar approach with patents as the unit of analysis (Fleming, 2001; Fleming and Sorenson, 2001), we estimated a negative binomial model using the PROC GENMOD procedure in SAS. As each individual needs to have accumulated a number of patents before his or her expertise profile can be accurately assessed, we considered only the patents filed by inventors who had at least 5 patents prior to filing the focal patent. A total of 5826 patents met this criterion.[7] Table 5 reports estimates of the effects of independent variables on each patent's forward citations.

Analysis 2. The second set of analysis examined the number of inventions generated by each inventor over a three-year window period. This analysis tests hypothesis 2, to examine how an inventor's breadth and depth of expertise at the beginning of a time period influences the number of patents that s/he generates in that period. Similar to Fleming et al. (2007), we split each inventor's career into three-year periods. The model analyzed nine window periods: 1976–1978, 1979–1981, 1982–1984, 1985–1987, 1988–1990, 1991–1993, 1994–1996, 1997–1999, and 2000–2002. Redefining the window periods, with the starting window period as 1977–1979 and 1978–1980, did not change the results.

The dependent variable for this analysis is the number of patents that the focal inventor has published during the three-year window period (#Patents$_t$). The independent variables are the breadth and depth of the focal inventor based on patents published prior to the beginning of the window period (Year t). As controls, we included the following variables: (1) #Years: number of years since the focal inventor has first published his/her first patent; (2) #Patents: number of patents published by the focal inventor prior to Year t, and (3) #Co-inventors: number of co-inventors for patents published prior to Year t. We logged the #Patents and #Co-inventors to achieve a normal distribution as the two variables were highly skewed. We also included a dummy for each UPC code that took on the value of 1 if that UPC code was the most frequent UPC code that the focal inventor published in prior to year t, to control for the possibility that researchers in some domain areas may generate more patents than others. Table 6 shows the descriptive statistics and correlations for the variables used in Analysis 2.

As the analysis was for a panel dataset with count data as the dependent variable, we used the GLIMMIX Procedure in SAS that allowed us to specify random effects and a multi-level structure with repeated measures nested within individuals. PROC GLIMMIX performs estimation for generalized linear mixed models, which extend the class of generalized linear models by incorporating random effects. Generalized linear models are used when the data are uncorrelated, but when observations exhibit some form of dependency. In our case, when repeated observations are taken from the same individual across time periods, the models fit by the GLIMMIX procedure extend the generalized linear models by incorporating correlations among the responses (Schabenberger, 2005). At the same time, it can model non-normal response distributions, including the negative binomial distribution when the dependent variable is in the form of count data.

For each period beginning in Year t, we excluded observations from individuals who had fewer than 5 patents prior to Year t, because each individual needs to have accumulated a number of patents before his or her expertise profile can be accurately assessed.[8] Based on this criterion, the dataset for this analysis included 3076 observations for 1249 individuals.[9] Table 7 reports estimates of the effects of key variables on the number of patents published by an inventor in each three-year window period.

Analysis 3. The third set of analysis examined how the breadth and depth of inventors' expertise influenced the probability that

[7] We adopted the approach of Fleming et al. (2007) to conduct further analysis to control for the possibility of selection bias. We first estimated a first-stage selection model (Heckman, 1976) to estimate the probability that the focal patent will have at least one inventor who published 5 or more patents prior to the patent. Using data from all observations, we estimated the first stage selection model using the following predictors: (1) number of inventors on the patent; (2) number of UPC the focal patent has been classified in; and (3) the application year of the patent. The inverse mills ratio generated in the first stage, which serves as a control for the probability that the focal patent will have at least one inventor who published 5 or more patents prior to the patent, is then entered into the estimation model used to test the hypotheses (Fleming et al., 2007). As the lambda coefficient was not significant, and the results did not differ with the inclusion of the ratio, we reported the results that did not include the inverse mills ratio.

[8] Further sensitivity analysis changing the criterion to four or six patents show that the results remain unchanged (for all three sets of analyses).

[9] Similar to analysis 1, we conducted further analysis to control for the possibility of selection bias. We first estimated a first-stage selection model (Heckman, 1976) to estimate the probability that an individual, at the beginning of a time period, would have accumulated 5 or more patents. Using data from all observations, we estimated the first stage selection model with the following predictors: (1) number of years since the focal inventor has first published his/her first patent; (2) the number of co-inventors prior to year t; (3) the average number of co-inventors per patent for patents published prior to year t; and (4) the UPC code in which the focal inventor publishes most frequently. The inverse mills ratio generated in the first stage was then entered in the model testing our hypotheses in the second stage. As highlighted by Fleming et al. (2007), the ratio serves as a proxy to control for the probability that the inventor will have more than 5 patents prior to each time period. As the lambda coefficient was not significant, and the results did not differ with the inclusion of the ratio, we reported the results without the inclusion of the inverse mills ratio.

Table 3
Description of control variables included in predicting forward citations of patents.

	Variable	Measure
1.	Mean Technology (Tech Mean)	We calculated the expected citations of technically similar patents – to control for differences in expected citations across patents in different UPCs. We begin by calculating the average number of citations that patents in each UPC, published in each year, receives as of 2006 – this serves as the proxy for the expected forward citation for patents published in each UPC in each year. Based on the UPC that the focal patent is classified in and the application year of the patent, we calculate the average expected forward citations for the focal patent. For example, if class 1 patents in year 1990 averages 3.0 cites per patent and class 18 patents in year 1990 averages 5.0 cites per patent, a patent published in year 1990, classified in one class of 1 and two classes of 18 would have an expected citation count of $(1/3) \times 3.0 + (2/3) \times 5.0 = 4.33$
2.	No of Prior Art Citations (Backward Cites)	Number of prior art citations made by the focal patent.
3.	Single-Class Dummy (Single Class)	Takes on a value of 1 if the focal patent is assigned to only one UPC.
4.	No of subclasses (#subclasses)	Number of focal patents' sub patent classes.
5.	Newest UPC	Minimum number of previous times that a UPC has been used to classify a patent, amongst the focal patent's UPCs (divided by 1000 for scaling).
6.	No of patent classes (#UPC)	The number of UPCs that the focal patent has been classified in.
7.	Average number of patents by inventors (Avg. #Patents)	Average number of patents published by inventors of a focal patent, prior to Year *t*.
8.	No of inventors with 5 or more patents prior to Year *t* (#Inv ≥ 5Patents)	As we only measured the expertise of inventors who had 5 or more patents, we included a variable measuring the number of inventors who had 5 or more patents prior to Year *t*.
9.	No of inventors with less than 5 patents prior to Year *t* (#Inv < 5Patents)	Number of inventors who had less than 5 patents prior to Year *t*.
10.	No of yrs since application (No Yrs)	Number of years that has elapsed since application year, as of 2007.

Table 4
Descriptive statistics for variables predicting forward citations of patents.

	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12
1. #FwdCites	11.96	18.60												
2. Avg. Breadth	10.47	5.42	−0.029											
3. Avg. Depth	0.63	0.18	0.020	−0.541										
4. Tech Mean	11.02	6.24	0.362	−0.122	0.065									
5. Backward Cites	33.54	32.09	−0.072	0.079	−0.017	−0.117								
6. Single Class	0.41	0.49	−0.075	−0.133	0.073	0.041	−0.042							
7. #Subclasses	5.99	4.41	0.066	0.157	−0.072	−0.072	0.048	−0.394						
8. Newest UPC	9.489	9.785	−0.181	−0.027	0.029	−0.229	0.131	0.411	−0.125					
9. #UPC	2.03	1.18	0.091	0.177	−0.099	−0.045	0.011	−0.729	0.563	−0.372				
10. Avg. #Patents	12.85	8.73	−0.156	0.647	−0.184	−0.264	0.248	−0.042	0.065	0.128	0.038			
11. #Inv < 5Patents	1.35	1.43	0.047	−0.033	−0.021	0.077	0.073	0.032	−0.019	0.073	−0.029	−0.059		
12. #Inv ≥ 5Patents	1.78	1.18	−0.100	0.133	−0.038	−0.207	0.328	−0.029	0.044	0.128	0.011	0.289	−0.014	
13. No Yrs	10.51	6.29	0.355	−0.034	0.048	0.399	−0.376	−0.065	0.043	−0.388	0.102	−0.334	−0.102	−0.314

Note. Correlations > |0.025| are significant at $p < 0.05$.

Table 5
Results of analysis predicting forward citations of patents.

	Model 1	Model 2	Model 3
Intercept	−0.022 (0.088)	−0.046 (0.099)	−0.105 (0.100)
Tech mean	0.089*** (0.003)	0.089*** (0.003)	0.091*** (0.003)
Backward cites	0.002*** (0.001)	0.002*** (0.001)	0.002*** (0.001)
Single class	−0.123** (0.046)	−0.122** (0.046)	−0.125** (0.046)
#Subclasses	0.012** (0.004)	0.012** (0.004)	0.013** (0.004)
Newest UPC	−0.003 (0.002)	−0.003 (0.002)	−0.002 (0.002)
#UPC	0.020 (0.021)	0.021 (0.021)	0.022 (0.021)
Avg. #Patents	−0.007*** (0.002)	−0.007* (0.003)	−0.007* (0.003)
#Inv < 5Patents	0.080*** (0.011)	0.081*** (0.011)	0.079*** (0.011)
#Inv ≥ 5Patents	0.049** (0.015)	0.049** (0.015)	0.054*** (0.015)
Application year	0.093*** (0.004)	0.093*** (0.004)	0.094*** (0.004)
Avg. breadth		0.002 (0.005)	−0.002 (0.005)
Avg. depth		0.302** (0.105)	0.187+ (0.111)
Avg. breadth * avg. depth			−0.052** (0.016)
Deviance	6569	6563	6558
Deviance difference (ΔDev)		6**	5**

Note. Standard errors are provided in parentheses; all significance tests are two-tailed, with significance indicated with the following conventions: $^{+}p < 0.10$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 6
Descriptive statistics for variables predicting no of patents generated in a 3-year period.

	Mean	S.D.	1	2	3	4	5
1. #Patents$_t$	2.86	3.39					
2. Breadth	9.52	5.48	0.24				
3. Depth	0.64	0.20	−0.07	−0.51			
4. #Years	12.41	6.82	−0.09	0.33	−0.22		
5. ln#Patents	2.20	0.54	0.35	0.67	−0.22	0.31	
6. ln#Co-inventors	2.02	1.21	0.24	0.32	−0.20	0.03	0.49

Note: Correlations > |0.03| are significant at $p < 0.05$.

individuals would have successful careers in 3M, providing a test for hypothesis 3. To assess whether an individual has a successful career in the corporation, we used two 3M organizational variables that indicates the contribution of inventors toward products and technological platforms that bring in significant sales and profits for the firm: (1) the organizational rank of the inventor in 3M; and (2) whether the individual has been given the Carlton Award, the prestigious "Nobel Prize" of 3M (Govindarajan and Lang, 2002).

Organizational rank. Technical employees in 3M are ranked on an organizational scale ranging from T1 to T7. For research scientists, most individuals with PhDs enter the organization at level T3. The T7 level refers to corporate scientists, who represent the highest-ranked research scientists in the company. Especially for promotion to the top two echelons – the research scientists most valued by the company, 3M places significant emphasis on evaluating inventors' contributions based on the commercial value that their inventions have generated. Based on our interviews with 3M research scientists, *31 of the 33 employees interviewed* said that the key criterion to achieve organizational ranks T6 and T7 is the amount of sales that the research scientist generates for the organization through his or her inventions. For example, one interviewee noted:

> "Sales numbers are a big thing, especially [for] promotions at T6 and T7 levels, I mean you definitely have to have a contribution that is very strong and contributed to projects that have made some money." (T6 Research Scientist)

Another interviewee provides a good overview of the different types of criteria affecting promotion for individuals at different organizational ranks:

> "Mainly the advancement of a person from T3 to T4 depends on their ability to have demonstrated that they can work collaboratively on a project with others in the company and that it has advanced to a stage where maybe some patents will be filed, maybe there's a business unit that is expressing some interest in it. . . And then to a T5, just probably more demonstrations of that in other areas. Advancing still to higher levels (T6 and T7), really the sales you can account for becomes the key factor." (T4 Research Scientist)

A review of the forms the human resource division requires as part of the promotion review packet further verified that individuals wishing to be considered for promotion to levels T6 and T7 had to indicate the financial impact they brought to the firm as a key component of the evaluation. The form required researchers to state the products their inventions contributed to, the corresponding sales amount and the role that the individual played in generating the product. A corporate scientist involved in the promotion process explained that it was not sufficient for an individual to successfully convert inventions into a single highly successful product. Rather, researchers need to be able to show consistent success in bringing their inventions to the market and thus contributing significantly to the revenue of the organization through several innovative products. Hence, an inventor's organizational rank was a good measure of that person's career success in the corporation and also an indicator of his or her continued success at generating commercially successful innovations. Based on these findings, we used the organizational rank of the inventor to proxy the career success of the individual as an innovator. Specifically, we differentiate between individuals who are ranked "T3–T5" (Rank = 1), "T6" (Rank = 2) and "T7" (Rank = 3) I Individuals ranked below T3 are seldom included in patents; hence they do not appear in our dataset. We made this distinction because promotion to T6 and T7 depended heavily on the business impact of their inventions, while promotion from levels T3 to T5 depended on many factors other than their business impact.

Carlton Award. To supplement this measure, we also included a measure of whether the inventor has received the Carlton Award, which is the highest form of recognition that 3M can provide its technical employees. It is usually awarded to employees who have made major technical contributions to technologies or products that generated significant sales and impact for the company. The award is sometimes nicknamed 3M's Nobel Prize for technical employees. The criteria for the award state that technical contributions "may be in the form of inventions, product

Table 7
Results of analysis predicting no of patents generated by an inventor in each period.

	Model 1	Model 2	Model 3
Intercept	−0.531*** (0.109)	−0.306* (0.138)	−0.321* (0.139)
#Years	−0.033*** (0.003)	−0.035*** (0.003)	−0.035*** (0.003)
ln#Patents	0.474*** (0.049)	0.404*** (0.058)	0.405*** (0.058)
ln#Co-inventors	0.087*** (0.022)	0.075*** (0.023)	0.076*** (0.023)
Application year	***	***	***
Most frequent UPCs	***	***	***
Breadth		0.011* (0.005)	0.011* (0.006)
Depth		−0.125 (0.109)	−0.153 (0.114)
Breadth * depth			−0.014 (0.015)
Deviance (−2log likelihood)	12,276	12,266	12,265
Deviance difference (ΔDev)		10**	1

Note. Standard errors are provided in parentheses; all significance tests are two-tailed, with significance indicated with the following conventions: $^+p < 0.10$, $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 8
Descriptive statistics for variables predicting rank of inventors as of year 2007.

	Mean	S.D.	1	2	3	4	5	6	7	8	9
1. Inventor rank	1.19	0.47									
2. Award	0.04	0.20	0.66								
3. Breadth	9.19	5.16	0.32	0.22							
4. Depth	0.63	0.20	−0.08	−0.02	−0.47						
5. $\#Years_{2007}$	19.97	9.43	0.25	0.19	0.27	−0.15					
6. R&D	0.20	0.40	0.13	0.11	0.18	−0.19	−0.02				
7. $\ln\#Patents_{2007}$	2.27	0.58	0.35	0.27	0.67	−0.15	0.11	0.10			
8. $\ln\#Co\text{-}inventors_{2007}$	2.36	0.92	0.19	0.13	0.38	−0.21	−0.25	0.07	0.55		
9. Avg. $\#Co\text{-}inventor_{2007}$	2.59	1.46	−0.09	−0.05	−0.07	0.03	−0.53	0.05	0.06	0.54	
10. #Years Recent $Patent_{2007}$	6.34	5.53	−0.03	−0.02	−0.11	0.08	0.61	−0.04	−0.33	−0.55	−0.47

Note. Correlations > |0.06| are significant at $p < 0.05$.

development, process improvements, new material technologies, new technology platforms, fundamental understanding, technical support, technical service, or technical leadership exemplified by vision and sponsorship for new products and technologies or by support of others embarking in new technical directions", and these contributions must "have significantly and positively impacted 3M's business performance".

As we were able to obtain the organizational rank of the inventors and the Carlton Award winners only as of 2007, we conducted the third analysis as a cross-sectional analysis as of year 2007 with individuals as the unit of analysis. The independent variables are the inventors' knowledge breadth and depth, based on the patents published by the inventors prior to Year 2007. We included several control variables, including (1) the total number of patents published by each inventor prior to year 2007 ($\#Patents_{2007}$); (2) the focal inventor's total number of co-inventors prior to year 2007 ($\#Co\text{-}inventors_{2007}$); (3) whether the inventor was in the corporate R&D group of 3M as of 2007 (R&D); and (4) the number of years since the focal inventor had first published his or her first patent as of 2007 ($\#Years_{2007}$); (5) the average number of co-inventors per patent for patents published prior to year 2007 (Avg. $\#Co\text{-}inventor_{2007}$); and (6) the number of years since the inventor has published his or her most recent patent as of 2007 (#Years Recent $Patent_{2007}$). Table 8 shows the descriptive statistics and correlations of the variables included in the analysis.

As inventors' rank is ordinal data with three levels, we applied the ordered probit regression analysis to predict inventors' rank. Whether an individual has received the Carlton Award is a binary variable; hence we applied the logistic regression to predict the probability that an individual would receive the Carlton Award. Similar to prior analyses, we considered only inventors who had at least 5 patents prior to 2007 (total of 1162 inventors).[10] Table 9 reports estimates of the effects of the above variables on the rank of each inventor, and Table 10 reports estimates of the effects of the variables on the probability of winning the Carlton Award.

[10] We also used Heckman's (1976) two-stage model to correct for sample selection bias. Using data from all observations, we estimated the first stage selection model using the following predictors: (1) whether the inventor was in the corporate R&D group of 3M (R&D); (2) the number of years since the focal inventor had first published his or her first patent; (3) the total number of co-inventors with whom t the focal inventor had published patents prior to year 2007; (4) the average number of UPC codes per patent for patents published prior to year 2007; and (5) the UPC code that the inventor published most frequently in prior to year 2007. The first stage selection model generated an inverse mills ratio, which serves as a control for the probability that the focal inventor has published five or more patents prior to Year 2007. The ratio was then entered into the estimation model used to test the hypotheses (Fleming et al., 2007). As the results did not differ with the inclusion of the ratio (which was also insignificant), we reported the results without the inclusion of the inverse mills ratio.

5.3. Results

For all three analyses, we used a step-wise approach to present our results. Model 1 was first estimated with only the control variables. Model 2 then added the main variables related to inventors' expertise. Finally, we included the interaction term for breadth and depth of inventors' expertise.[11] We examined the significance of the incremental variance explained by examining the differences between the deviance statistics (Δdev) for each pair of nested models. Δdev is twice the negative log-likelihood, and has a chi-square distribution with the difference in number of parameters between models to be estimated as the degrees of freedom.[12]

Predicting patent forward citations. We first examined how inventors' expertise influenced their ability to generate technically influential inventions. Table 5 shows that inventors' depth of expertise significantly influenced inventor's average forward citations (Table 5, Model 2, $\beta = 302$, $p < 0.01$). This provides support for H1, which states that individuals with greater depth of expertise are more likely to generate technically influential innovations. Interestingly, Table 5 also shows that inventors with both high depth and high breadth of expertise appear to be unable to achieve their potential in creating technically influential inventions (Table 5, Model 3, $\beta = -0.052$, $p < 0.01$). This may occur because – when it came to generating technically influential inventions – depth of expertise was critical to focus the inventors' energy and efforts, while broad expertise may have been a distraction rather than an advantage.

Predicting number of patents generated. Next, we examined how an inventor's expertise profile influenced his or her ability to generate more inventions in the form of patents. Table 7 shows that inventors with greater breadth of expertise tend to have more patents in each time period (Table 7, Model 2, $\beta = 0.011$, $p < 0.05$), providing support for H2. Neither inventors' depth of expertise (Table 7, Model 2, $\beta = -0.125$, $p > 0.10$) nor the interaction between breadth and depth of expertise (Table 7, Model 3, $\beta = -0.014$, $p > 0.10$) significantly influenced the number of patents per period.

Predicting inventors' organizational rank and probability of winning the Carlton Award. We then examined how inventors' expertise influenced their career success, an indication of the value they brought to their organizations by converting their inventions into commercially successful products. Using inventors' organizational rank as the dependent variable, Table 9 shows that inventors'

[11] The significance of the coefficients generated by the probit, logistic and negative binomial analyses (Tables 5, 9 and 10) are tested with the Wald statistic is: $(\hat{\theta} - \theta_0)^2 / var(\hat{\theta})$, which is compared against a chi-squared distribution.

[12] All models were inspected for multicollinearity using the condition index and the variance inflation factors. All the models have variance inflation factors less than four, and condition index less than 22. As can be seen in Tables 5, 7, 9 and 10, there were also no sign flips with the additions of variables to the model. These provide evidence that there are no significant multicollinearity issues with the analyses.

Table 9
Results of analysis predicting rank of inventors as of year 2007.

	Model 1	Model 2	Model 3
Intercept 1	−4.814*** (0.335)	−4.634*** (0.393)	−4.539*** (0.397)
Intercept 2	1.046*** (0.084)	1.053*** (0.084)	1.059*** (0.085)
#Years$_{2007}$	0.048*** (0.007)	0.049*** (0.007)	0.049*** (0.007)
R&D	0.343**(0.113)	0.369** (0.116)	0.369** (0.116)
ln#Patents$_{2007}$	0.409**(0.125)	0.291* (0.147)	0.272+ (0.148)
Ln #Co-inventors$_{2007}$	0.418** (0.130)	0.455*** (0.134)	0.459*** (0.136)
Avg. #Co-inventor$_{2007}$	−0.131* (0.061)	−0.137* (0.061)	−0.142* (0.062)
#Years Recent Patent$_{2007}$	−0.016 (0.013)	−0.019 (0.013)	−0.019 (0.013)
Breadth		0.016 (0.014)	0.028+ (0.015)
Depth		0.580+ (0.307)	0.563+ (0.310)
Breadth * depth			0.124* (0.049)
Deviance (−2log likelihood)	956	952	940
Deviance difference (ΔDev)		4	11***

Note. Standard errors are provided in parentheses; all significance tests are two-tailed, with significance indicated with the following conventions: +$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 10
Results of analysis predicting Carlton award as of year 2007.

	Model 1	Model 2	Model 3
Intercept	−10.331*** (1.006)	−10.210*** (1.176)	−10.003*** (1.194)
#Years$_{2007}$	0.123*** (0.020)	0.128*** (0.020)	0.129*** (0.020)
ln#Patents$_{2007}$	1.094*** (0.322)	0.920* (0.391)	0.822* (0.399)
Ln #Co-inventors$_{2007}$	0.654+ (0.348)	0.769* (0.364)	0.769* (0.368)
Avg. #Co-inventor$_{2007}$	−0.047 (0.185)	−0.081 (0.188)	−0.063 (0.190)
#Years Recent Patent$_{2007}$	0.029 (0.031)	0.023 (0.032)	0.022 (0.032)
Breadth		0.018 (0.030)	0.056 (0.034)
Depth		1.496+ (0.859)	1.211 (0.883)
Breadth * depth			0.231* (0.100)
Deviance (−2log likelihood)	426	422	411
Deviance difference (ΔDev)		4	11***

Note. Standard errors are provided in parentheses; all significance tests are two-tailed, with significance indicated with the following conventions: +$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

breadth of expertise did not significantly influence their organizational rank (Table 9, Model 2, $\beta = 0.016$, $p > 0.10$), while inventors' depth of expertise had only a marginally significant influence (Table 9, Model 2, $\beta = 0.580$, $p < 0.10$). Inventors with both high breadth and depth of expertise, however, were more likely to hold higher organizational rank (Table 9, Model 3, $\beta = 0.124$, $p < 0.05$).

Next, we predicted the probability that inventors would receive the Carlton Award, using that award to proxy the value that each inventor brought to the organization. The results are similar to those predicting rank. Table 10 shows that inventors' breadth of expertise did not significantly influence their probability of winning the award (Table 10, Model 2, $\beta = 0.018$, $p > 0.10$), while inventors' depth of expertise had only a marginally significant influence (Table 10, Model 2, $\beta = 1.49$, $p < 0.10$). Inventors with both high breadth and depth of expertise, however, were more likely to win the Carlton Award (Table 10, Model 3, $\beta = 0.231$, $p < 0.05$). Both sets of analyses provide support for H3, which states that individuals with greater depth and breadth of expertise are more likely to achieve career success in 3M.

6. Discussion

The results of our analysis show that an inventor's expertise profile is important in influencing his or her success as both an inventor and an innovator. Our findings advance insights offered by previous research on expertise and innovation in several ways.

First, we presented both the theoretical arguments and empirical evidence to show that individuals' breadth and depth of expertise should be conceptualized as two separate and orthogonal dimensions. Indeed, the traditional conceptualization of the renaissance man – who has deep expertise in many different domain areas – is an ideal that is difficult to achieve. What we found, however, was that the polymath inventors in 3M had deep expertise in one or more core domain areas and then they applied this expertise widely by integrating it with other technologies in new domain areas, thus gaining expertise in the new domain areas.

We conducted additional analysis (see Appendix B online) to examine how generalist, specialist and polymath inventors changed in their expertise profile over time. Our analysis showed that specialists' breadth and depth remain relatively unchanged across time. Polymath inventors typically began their careers by specializing, maintaining high depth and low breadth of expertise. As we had conceptualized, over time, their breadth increased and their depth decreased marginally. Generalist inventors, on the other hand, start with a lower depth of expertise, which steadily decreases over time as their gain expertise in more domain areas. Overall, this analysis shows that our conceptualization of how a polymath inventor gained expertise over time – starting out specializing in their core areas of expertise, and learning new areas as they start to apply their core expertise to new areas – appeared to be verified by the data.

A recent study by Jones et al. (2008) found that increasing technological progress has led to an increase in the amount of education and depth of expertise required before scientists can generate their first invention. The requirement for depth of expertise in each discipline increases as technological progress amplify the stock of knowledge that innovators must be aware of and build upon before they can achieve progress in generating new inventions. This points to the tendency that inventors will become more specialized, or they will require the help of other specialists if they need to integrate knowledge from other fields (Jones, 2011). It also makes it increasingly costly to master several different areas of knowledge and expertise. As a result, the proverbial Renaissance Men are expected to become even scarcer.

Interpreted in the context of these findings, our results are even more significant in the following ways. First, our results highlight a way that specialists can expand their knowledge to become polymaths – by anchoring themselves in their core technologies and apply and integrate these technologies with new areas, thus also learning about new technological domains. This shows that the increase in the initial hurdle for invention may not only lead to narrow specialization of expertise by inventors, but also provide the incentive for these inventors to leverage on their inventions through wide application and integration with other technologies. Second, our study of 3M inventors show that a corporate environment like 3M's can be conducive to cultivate generalists and polymaths, due to the diversity of business, the emphasis on sales, and the philosophy that the company, rather than individual business units, owned the technology. As highlighted in prior research, the need for generalists and polymaths will increase as specialization narrows, as those who span areas of knowledge will not only improve communication between specialist team members, but will also be able to effectively broker and integrate multiple technologies. Hence, there is scope to learn from an organization like 3M how generalists and polymaths can be cultivated.

Second, we recognize that becoming a successful inventor, who creates technically important inventions, require different characteristics than those needed to become a successful innovator, who brings value to a commercial organization through the revenue contribution of his or her inventions. Prior research on innovation tends to focus only on the technical success of an invention or an inventor (Audia and Goncalo, 2007; Fleming et al., 2007) – examining the forward citations or novelty of inventions. Our results show that breadth of expertise helps an inventor to generate many inventions, but depth of expertise helps an inventor to generate technically influential inventions. Both breadth and depth of expertise are required for an inventor to be successful and valued in a commercial corporation.

While one may argue that it is intuitive to expect that those with both breadth and depth of expertise (polymaths) will be more successful that those with only breadth (generalists) or only depth (specialists) of expertise, we argued and showed, that inventors with different expertise profiles – generalists, specialists and polymaths – have different impacts on the organization. We conducted additional analysis (see Appendix C online) to show that it was not a case of the more the better. Rather, different inventors contributed to 3M in different ways. The specialists contributed to 3M by producing the most technologically influential inventions. The generalists contributed by producing many ideas and patents. The polymaths contributed not only by generating inventions, but applying these inventions widely to multiple parts of the organization, integrating with multiple technologies, thus becoming the most valued scientists of 3M.

While prior research on the psychology of science has provided rich insights into the individual psychological processes leading to creativity in science, this research does not focus on the concrete outcomes of individuals' cognitive differences. Prior research has also only examined the outcomes of individual depth or breadth of expertise as a single dimension. We thus contribute to this area of research by explaining how individuals with different expertise profiles approach the innovation process differently, and how their expertise profiles influence their success in generating inventions and innovations.

Third, by examining the case of 3M in depth and studying in detail the inventors' expertise profiles, how they approach the innovation process, how that influences the value they bring to the firm, as well as characterizing the 3M practices and aspects of the environment that cultivate different types of inventors, we provide detailed information about how a successful and innovative firm effectively manages its inventors and how the various organization practices influence the value that individuals bring to the firm.

6.1. Implications for practice

Our study has several implications for practice. First, the identification of inventors with different types of expertise profiles (specialists, generalists, and polymaths) demonstrates that an organization's most valuable inventors can come in different shapes and sizes. A key take away for practitioners, therefore, is that organizations should not necessarily cultivate all their inventors to become polymath inventors. Instead, an organization should build an ecosystem made up of specialist, generalist and polymath inventors. Organizations can also consider these archetypes when they make hiring decisions for inventors. An individual with diverse interests, who likes to work on different and new things, may be a good candidate for a generalist, whereas an individual with impeccable focus and perseverance to keep working on a single problem could be a potential specialist. As for potential polymath inventors, we suspect such individuals would need to be cultivated, which means that organizations need to provide room for individuals to develop both breadth and depth simultaneously, if they have the inclination to do so.

Our findings also highlight the need for individual inventors to recognize their expertise profiles and their corresponding strengths and weaknesses. It is important for individuals to recognize that their expertise enables them to contribute in distinct ways to the organization; hence they should approach the innovation process in ways that effectively leverage their strengths and complement their weaknesses. Our qualitative interviews identified strategies that were particularly useful for individuals with different expertise profiles, which provide significant practical implications to individual inventors. For specialists, one may have assumed that specialists should continue to work in the areas where they were trained in order to leverage the deep technical knowledge that their training and education provide. Yet we found that specialists who bring the most value to the firm are those who have skills that are valued by the firm. Hence, specialists should be willing to learn and develop new areas of expertise and entrench themselves as experts in the areas of expertise most required by the firm. Generalists, on the other hand, should focus on ways to bring value to the firm by focusing on applications of technologies, and by developing a set of fundamental skills that they are able to bring across domains, even while they move often from one domain to another. Finally, polymaths get the most out of both their breadth and depth of expertise when they leverage their expertise to evaluate the potential of ideas, and to champion technologies in their core domains for wide application, integrating with technologies in multiple domains.

In addition, it is important for managers to recognize the archetypes that characterize the particular inventors they manage, leveraging their strengths and managing their weaknesses accordingly. Our qualitative study provides significant insights into the organizational environment that are conducive to inventors of different profiles. These insights provide some guidance to managers and firms on managing inventors of different archetypes. Specifically, specialists need to be given the space and time to work on potentially high impact inventions, and be given chances to fail in the process. Generalists, on the other hand, flourish when they have the opportunity to work on a broad range of related domains and in a collaborative environment. Finally, the organization provides the most incentive for polymaths to develop and flourish when they put emphasis on the importance for inventors to generate sales from their inventions, thus providing the impetus for inventors to get the most out of inventions in their core domains via wide applications and integrations with other technologies.

6.2. Limitations

The findings of this study should be interpreted within some limitations. First, our measures and conceptualizations of breadth and depth of expertise focus on inventors' knowledge in technical areas. Our interviews highlighted other types of knowledge that are also important for successful innovations. In particular, knowledge about customer needs and also about manufacturing capabilities and constraints may be especially helpful. Nevertheless, examining inventors' technological expertise as we have done enables us to conceptualize and operationalize our constructs. In future research, it would be fruitful to examine the conceptual and theoretical issues pertinent to the consideration of other types of expertise.

Second, we tested our third hypothesis only from a cross-sectional perspective, as we were able to obtain the organizational data on rank and awards as of a single point in time (as of 2007). We acknowledge that an individual's expertise profile does not remain static and would change across time; the influence of one's expertise may also change at different stages of the inventor's career. Hence, it may be interesting for future research to examine whether and how an inventor's expertise would affect the innovation process across time.

Third, as we made use of patent data to measure the breadth and depth of inventors' expertise, we were able to include data only on inventors with at least 5 patents. This effectively narrowed our sample to the more productive inventors in 3M, excluding the less experienced inventors. However, excluding this group of inventors is not expected to change our results, as we saw significant variance in the expertise and dependent variables for the group of inventors who were included in the analysis. In future research, it would be fruitful to measure expertise in a more encompassing manner that can also include less productive inventors (perhaps via organizational patent proposal submissions instead of patents).

Finally, as we examined a single case of one organization, the conclusions derived are likely less generalizable to firms with different characteristics. We believe, however, that our findings will apply to other large diversified firms, with significant emphasis on the translation of R&D work into commercial value for the firm. Most commercial firms are facing a more competitive environment and increasing demands from shareholders to exhibit growth, and one key way to achieve that is through new product development and introductions. Hence, R&D departments of commercial firms are facing increasing pressures on the output of the innovation pipeline (Festel et al., 2010). As a result, similar to 3M, commercial firms are now placing significant emphasis on ensuring that their R&D staff contribute toward the sales of products. Moreover, other large firms with a diversified portfolio of products will similarly be able to provide an environment for generalists and polymaths to flourish, in addition to specialists.

7. Conclusion

This study examines how an inventor's expertise profile influences his or her success both as an inventor and an innovator, through a case study of inventors in 3M. Our findings contribute to the literature on innovation by showing that breadth of inventor expertise relates to the generation of inventions, but depth of inventor expertise is required to generate technically influential patents. Finally, both breadth and depth of expertise are required to effectively convert inventions into commercially successful products that bring sales and value to the organization.

Acknowledgements

The authors gratefully acknowledge the research assistance of Elaine Cheung and the participation of all 3M research scientists who generously shared their experiences and insights with the research team. This study was supported by a research grant from the Nanyang Technological University. The views and opinions expressed in this study are those of the authors.

Appendix. Supplementary data

Supplementary data (Appendices A, B and C) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.respol.2013.10.009.

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