To Complete a Puzzle, You Need to Put the Right Pieces in the Right Place

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Chapter 4. Does Going-Together Always Lead to Better Solutions?

An Exploration of Challenge-Based R&D Projects

Abstract: To tackle important grand societal challenges, government institutions initiate large-scale programs in which organizations participate in challenge-based R&D projects, aimed at solving extant technological problems within a specific field. The literature on grand challenges often implicitly assumes that organizations should formally involve partners in these projects – i.e. go-together – rather than proceeding independently – i.e. go-alone. They argue that the main advantage of going-together is that it increases the potential to generate high-quality technological solutions by merging partners' heterogeneous knowledge pool. In this study, we relax the assumption that going-together is always more productive than going-alone in terms of generating high-quality technological solutions – i.e. problem-solving performance. Specifically, we argue that that not every organization is able to translate potential into realized knowledge recombination opportunities. Firstly, we formulate a baseline hypothesis, in which we expect that problem-solving performance is higher, on average, when going-together than going-alone. Secondly, we hypothesize that the ability to translate potential into realized knowledge recombination opportunities when going-together is contingent upon the focal organization's institutional background, internal knowledge pool size, and challenge-based R&D project portfolio size. Analysing a unique sample of 414 challenge-based R&D projects within the Department of Energy's Hydrogen and Fuel Cells Program over a 14-year time period (2003-2016), we generally find support for our theoretical predictions. We contribute to the literature on grand challenges and open innovation by showing that the often-assumed performance edge of going-together over going-alone does not materialize for every organization. Based on these findings, we also encourage policy-makers to more carefully design grand societal challenge programs, and not treat going-together as some panacea for innovation.

This chapter was written together with Dries Faems and Pedro de Faria.

4.1. Introduction

Large-scale funding programs have been increasingly used by governments to stimulate the creation of innovative solutions aimed at tackling significant societal challenges such as climate change, demographic changes or smarter infrastructure (Howard-Grenville *et al.,* 2014; Olsen *et al.,* 2016). Within these programs, firms, universities and other organizations participate in challenge-based R&D projects, aimed at overcoming existing technological barriers within a particular technological field. Within these R&D projects, organizations strive to develop technological solutions with the objective of meeting certain technological targets by a certain point in time.

In line with the open innovation paradigm (Chesbrough, 2006), extant research on grand challenges strongly emphasizes the advantages of collaborative strategies to generate high-quality solutions for technological problems (Howard-Grenville *et al.,* 2014; Olsen *et al.,* 2016). The core argument within this paradigm is that collaboration allows organizations to access partners' heterogeneous knowledge, creating opportunities for synergistic knowledge recombination (e.g. Olsen *et al.,* 2016), resulting into solutions that the organization could not have generated individually. In other words, going-together in challenge-based R&D projects triggers unique knowledge recombination opportunities that are not available when going-alone. However, whereas research on grand challenges emphasizes these potential knowledge recombination opportunities, it remains surprisingly silent on organizations' ability to actually realize these opportunities. As a result, there seems to be an implicit assumption that going-together is always more productive in terms of generating high-quality technological solutions than going-alone. Relying on the established alliance literature, we, however, argue that realizing collaborative recombination opportunities may be highly challenging to some organizations. An exploration of when going-together leads to superior outcomes in challenge-based R&D projects therefore seems to be necessary.

The aim of this study is therefore to shed light on the conditions under which going-together substantially outperforms going-alone in challenge-based R&D projects in terms of generating high-quality solutions to extant technological problems. Using knowledge-based view (KBV) theoretical insights (Das & Teng, 2000; Galunic & Rodan, 1998; Kogut & Zander, 1992), we argue that not every organization has the ability to realize recombination opportunities emerging from going-together. Specifically, the benefits of going-together hinge on the focal organization's ability to identify, retrieve, and recombine components across different organizational boundaries, which can be challenging to certain organizations (Miller *et al.,* 2007; Rosenkopf & Nerkar, 2001; Zahra & George, 2002). In line with this contention, we argue that three characteristics of the focal organization influence the relative problem-solving performance – i.e. the ability to generate high-quality solutions to extant technological problems – of going-together compared to going-alone. First, we argue that focal organizations with different institutional backgrounds (i.e. firms and research organizations) possess certain characteristics that influence their ability to translate potential into realized knowledge recombination opportunities when going-together. In this respect, we expect that the positive performance gap between going-together and going-alone will be larger for research organizations than for firms, as we argue that research organizations tend to be more capable of recombining partners' component knowledge. Second, we posit that when the focal organization's internal knowledge pool is larger, its ability to identify and retrieve partners' valuable components will be higher (Cohen & Levinthal, 1990), increasing the positive performance gap between going-together and going-alone. Third, we expect that when the focal organization is concurrently engaged in a higher number of challenge-based R&D projects (i.e. larger R&D project portfolio), the performance gap between going-together and going-alone will decrease, because fewer resources will be available to realize recombination opportunities within single projects (Levinthal & Wu, 2010).

We investigate these expectations on 414 government-supported challenge-based R&D projects from the Hydrogen and Fuel Cells Program using unique data from the Department of Energy (DOE) over a 14-year time period (2003-2016). This database is particularly suitable to test our theoretical predictions since organizations within this program can opt to go-alone or go-together in challenge-based R&D projects. We operationalize this dichotomy by examining whether or not the project leader involves formal collaboration partners in the project. Moreover, in contrast to prior studies studying collaborative strategies, we do not infer project performance from organization-level performance, but rather capture problem-solving performance at the project-level, relying on objective and yearly project evaluations of expert peer reviewers.

Our findings indicate that going-together, on average, outperforms going-alone, suggesting that collaborative strategies indeed can provide unique knowledge recombination opportunities for solving particular R&D challenges. However, contrary to expectations, we find that the positive performance gap between going-together and going-alone is larger for firms than for research organizations, suggesting that, as leading entities, firms are more able to reap collaborative recombination opportunities in challenge-based R&D projects than research organizations. Moreover, in support of our theoretical arguments, we find that the positive performance gap between going-together and going-alone becomes larger when the focal organization has a larger internal knowledge pool. Finally, contrary to expectations, we find that the positive performance gap between going-together and going-alone initially widens as the focal organization's R&D project portfolio becomes larger. However, beyond a certain tipping point, the positive performance gap between going-together and going-alone decreases as the focal organization's R&D project portfolio becomes larger.

This study makes several important theoretical and practical contributions. Theoretically, we contribute to the literature on grand challenges and open innovation by underlining the fact that not every organization is able to fully reap the problem-solving benefits of going-together. In doing so, we provide a more nuanced perspective regarding the often-assumed benefits of going-together compared to going-alone in terms of generating valuable technological solutions. Our findings provide evidence that certain organizations – most notably research organizations and focal organizations with a small internal knowledge pool – are substantially less able to leverage collaborative knowledge recombination opportunities. These empirical findings also contribute to practice by pointing out that more careful consideration should be given to how challenge-based R&D projects are configured. Instead of treating going-together as a panacea for challenge-based R&D endeavors, it should be recognized that not all organizations are able to benefit from this problem-solving approach. Hence, we encourage policy-makers to more carefully design programs targeting societal grand challenges, paying careful attention to which type of organization is most capable of solving particular technological problems.

4.2. Theory and hypotheses

In this section, we discuss the relative problem-solving performance benefits of going-together compared to going-alone in challenge-based R&D projects. Challenge-based projects are projects in which a focal organization searches for high-quality technological solutions to extant critical technological problems (e.g. costs or durability of a particular material) within the framework of a grand societal challenge. To tackle these technological problems, focal organizations within challenge-based R&D projects can opt to go-together, involving formal partners to assist with problem-solving activities, or go-alone, conducting problem-solving activities without involvement of formal partners. In the following section, we formulate a baseline hypothesis in which we expect that problem-solving performance will be higher when the focal organization is going-together rather than going-alone. Subsequently, grounded in KBV insights, we explore three characteristics of the focal organization that might influence the size of the positive problem-solving performance gap between going-together and going-alone: (i) the institutional background of the focal organization, (ii) the focal organization's internal knowledge pool size, and (iii) the focal organization's R&D project portfolio size.

4.2.1. The knowledge recombination benefits of going-together

In challenge-based R&D projects, technological problems are addressed by recombining knowledge components into novel technological solutions (Galunic & Rodan, 1998; Fleming, 2001). Here, the adopted conceptualization of knowledge components comprises different "bits of knowledge or matter (Fleming & Sorenson, 2004: 910)" that can be used to develop new technological solutions. For example, the cost-efficiency of fuel cells was recently dramatically improved through a joint development effort between Ballard Power Systems and Nisshinbo Holdings, in which they created a non-platinum catalyst through recombining component knowledge of (i) carbon alloy materials, (ii) oxygen-reduction, and (iii) electrocatalysts (Banham *et al.,* 2017). The ability of the focal organization to generate useful technological solutions therefore depends largely on the availability of components. When too few components are available to generate interesting combinations, the focal organization runs the risk of being unable to adequately address technological problems at hand – i.e. the knowledge pool is dried-out (Fleming, 2001; Ahuja & Katila, 2004).

One means by which a focal organization can expand its component set is by participating in interorganizational collaboration (Grant & Baden-Fuller, 2004; Hamel, 1991; Rosenkopf & Almeida, 2003). Effectively, by merging various organizations' heterogenous knowledge pools, collaboration increases the set of available knowledge components that can be potentially used in new combinations and thereby makes it easier to find unique solutions to technological problems (Phelps, 2010). These complementary benefits exist because organizations develop technological competences in path-dependent and highly idiosyncratic ways (Nelson & Winter, 1982), implying that no two knowledge pools are ever completely identical (Yayavaram & Ahuja, 2008). Consequently, when merging the heterogeneous knowledge pools of partners, new combinations can be created that could not be developed by each partner independently (Das & Teng, 2000; Harrison *et al.,* 2001). By accessing the knowledge pool of other organizations via going-together, the focal organization will therefore be able to address extant technological problems more adequately, than when it is going-alone. Based on this theoretical mechanism, we formulate the following baseline hypothesis:

H1: Problem-solving performance is higher when the focal organization is going-together rather than going-alone

4.2.2. Organizations' abilities to realize potential recombination opportunities

Our baseline expectation is that going-together creates more potential recombination opportunities than going-alone, allowing focal organizations to solve extant technological problems more effectively when going-together compared to going-alone. Therefore, we assume that a larger positive problem-solving performance gap between going-together and going-alone indicates that the focal organization was able to translate the potential recombination opportunities of going-together into realized recombination opportunities to a larger extent. We expect, however, that the ability to realize these collaborative recombination opportunities is not equal for every organization. Even when organizations have access to the same set of components, there may be much variation in the extent to which they are able to use these components to develop valuable new technological solutions (Wuyts & Dutta, 2014; Zahra & George, 2002). In particular, organizations require abilities to identify valuable component knowledge in the partner's knowledge pool, retrieve it into the knowledge pool by developing a solid understanding of its technological characteristics, and, finally, develop high-quality solutions based thereupon by synergistically recombining it with other components (Fleming & Sorenson, 2001; Zahra & George, 2002). If they lack these abilities, focal organizations may either focus on the wrong components, be unable to retrieve the component knowledge, or be unable to realize valuable synergies based on the component, all of which may lead the focal organization to generate technological solutions of lower quality (Hargadon & Sutton, 1997; Nemet & Johnson, 2012).

Applying these insights, we argue that, in order to realize the potential recombination benefits of going-together, organizations should be able to identify, retrieve and recombine external components situated within partners' organizational boundaries (Grigoriou & Rothaermel, 2017; Lane & Lubatkin, 1998; Wuyts & Dutta, 2014). Organizational boundaries often present important barriers to extramural knowledge recombination, as they impede the focal organization's ability to retrieve accurate and complete information about external components (Galunic & Rodan, 1998; Miller *et al.,* 2007; Rosenkopf & Almeida, 2003; Sorenson *et al.,* 2006). Our baseline expectation is that going-together leads to higher problem-solving performance than going alone, by means of creating opportunities to access and exploit a larger and more diverse set of components to generate new technological solutions. Consequently, in case the organization is unable to span organizational boundaries in knowledge recombination, the problem-solving performance of going-together will be closer to that of going-alone (i.e. the available component set, in both situations, will be highly similar).

At the same time, certain organizations possess abilities to more effectively identify, retrieve and recombine external component knowledge than others (Bos *et al.,* 2017; Grigoriou & Rothaermel, 2017; Lane & Lubatkin, 1998; Wuyts & Dutta, 2014). In the following section, we follow these prior studies, and argue that three distinct characteristics of the focal organization are associated with these particular abilities. First, we expect that, since they are generally better able to identify, retrieve and recombine external component knowledge, research organizations have an edge over firms in terms of benefiting more from going-together compared to going-alone. Second, we expect that the larger the focal organization's internal knowledge pool, the larger the relative performance benefits of going-together compared to going-alone. Third, we argue that the focal organization's R&D project portfolio size (i.e. number of concurrent R&D projects) decreases the positive performance gap between going-together and going-alone.

Focal organization's institutional background. To translate potential into realized knowledge recombination benefits of going-together, organizations require abilities to identify, retrieve and recombine external component knowledge, creating synergies between partners' knowledge pool and their own (Das & Teng, 2000). These abilities, we argue, depend largely on the institutional role that the focal organization fulfills. Therefore, in this hypothesis we argue that research organizations are more able than firms to translate potential into realized recombination opportunities when going-together, impacting the relative problem-solving benefits of going-together compared to going-alone.

We expect that research organizations are highly capable of translating potential into realized recombination opportunities when going-together. This is principally because their institutional mission is to create and diffuse new scientific and technological knowledge (Cyert & Goodman, 1997), which (i) increases their appreciation of external knowledge and (ii) increases their willingness to actively collaborate and share knowledge with external parties. First, given their strong interest in diffusing new knowledge, research organizations are often strongly embedded within a broader research community. Indeed: "the central constituency for most university researchers lies outside the organization, in their professional reference group (Cyert & Goodman, 1997: 48)". Hence, research organizations are usually more outward- than inward-oriented (Trajtenberg, Henderson, Jaffe, 1997), concomitantly implying a higher level of receptiveness towards external knowledge. Second, as we know from research on social networks, knowledge diffuses more rapidly via collaboration networks (Fleming *et al.,* 2007). Therefore, it is expected that research organizations have strong incentives to collaborate and share their knowledge with partners. This increases the likelihood that knowledge diffuses more broadly and rapidly, which is advantageous for the research organization. Additionally, the research organization's willingness to share its own knowledge is likely to trigger reciprocal knowledge sharing on the partner's side, leading to higher synergistic knowledge recombination benefits (Das & Teng, 2000; Lane & Lubatkin, 1998).

In terms of appreciation of external knowledge and willingness to collaborate and share knowledge with partners, firms are very different from research organizations. Indeed, firms are profit-seeking organizations that tend to be more self-interested when engaging in knowledge sourcing, principally using it to create or sustain a competitive market position (Barney, 1991; Grant, 1996). As a corollary, firms usually prefer to be more self-reliant, relying principally on internal knowledge sources when possible (Srivastava & Gnyawali, 2011), as this minimizes the risks of exposing core technologies to external partners or becoming dependent for continuity on other organizations (Cassiman & Veugelers, 2002; Grimpe & Kaiser, 2010). Given this inward-orientation, firms also tend to suffer more often than research organizations from the not-invented-here syndrome (NIH) (Katz & Allen, 1982), whereby their receptivity towards external component knowledge is substantially lower than that of internal component knowledge (Fabrizio, 2009).

Taken together, we have two reasons to expect that research organizations will benefit relatively more from going-together than going-alone compared to firms: (i) research organizations have a higher appreciation of external component knowledge, implying that they will make more efforts to actively learn from external partners and (ii) it is more likely that, when research organizations collaborate with partners, knowledge is reciprocally shared, leading to the realization of synergistic benefits between partners' knowledge pools (Lane & Lubatkin, 1998)[1]. We hypothesize:

[1] For the sake of clarification, here we hypothesize that the relative problem-solving performance increase between going-together and going-alone is higher for research organizations than for firms. To illustrate this, consider a firm that has a performance of 200 when going-alone and 220 when going-together, and a research organization that has a performance of 100 when going-alone and 120 when

H2: The positive problem-solving performance gap between going-together and going-alone is larger for research organizations than for firms

Focal organization's internal knowledge pool. In this hypothesis, we argue that the size of the focal organization's internal knowledge pool – i.e. the quantity of technological solutions that the focal organization has successfully created within prior challenge-based R&D projects – influences the positive performance gap between going-together and going-alone. This influence is driven by two main theoretical mechanisms.

First, *ceteris paribus*, the larger the focal organization's internal knowledge pool, the more likely it is that the contents of this knowledge pool overlap with that of partners. As we know from prior studies (Lane & Lubatkin, 1998; Sampson, 2007), overlap in technological competences allows for easier communication between partners, improving the retrievability of components. That is, improved communication channels allow the focal organization to develop a more thorough understanding of components' recombination characteristics (Henderson & Clark, 1990; Sorenson *et al.,* 2006). Second, focal organizations with larger internal knowledge pools have more experience with creating high-quality solutions. Equipped with this experience, focal organizations are able to more rapidly and effectively identify valuable components in the partners' knowledge pool which they can subsequently use to create high-quality technological solutions (Henderson & Cockburn, 1994 Lewin *et al.,* 2011; Wuyts & Dutta, 2014). In this way, these focal organizations may circumvent a lot of the time-costly trial-and-error processes that lesser experienced focal organizations have to go through to achieve the same outcome (Katila & Ahuja, 2002; Fleming, 2002). Taken together, we hypothesize:

H3: The focal organization's internal knowledge pool size increases the positive performance gap between going-together and going-alone

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going-together. In this hypothesis, we argue that the relative problem-solving performance benefits of going-together compared to going-alone are higher for research organizations (i.e. difference between 120 and 100) than for firms (i.e. difference between 220 and 200). However, we are not comparing the difference in problem-solving performance between research organizations that go-together and firms that go-together (i.e. 120 versus 220).

Focal organization's R&D project portfolio. Numerous organizations participate in several challenge-based R&D project at the same time (Eggers, 2012; Henderson & Cockburn, 1996). Hence, single challenge-based R&D projects are often nested within a portfolio of challenge-based R&D projects at the organizational level. In this hypothesis, we argue that when the focal organization's portfolio of challenge-based R&D projects becomes larger, the positive problem-solving performance gap between going-together and going-alone will decrease.

By concurrently engaging in more challenge-based R&D projects, the focal organization's scarce resources are dispersed across a larger number of projects. As a result, the existing resource base of the focal organization is more likely to be overextended, leading to resource constraints at the project-level. This is especially problematic because resources that are used in challenge-based R&D projects tend to be non-scale free – i.e. their opportunity costs are positive (Levinthal & Wu, 2010). For example, the use of a fuel cell test facility in one project generally implies that other fuel cell projects cannot simultaneously make use of this same facility. The same holds for the allocation of human capital: R&D scientists can only be deployed in so many projects, before their productivity significantly declines. Thus, when the focal organization's challenge-based R&D project portfolio is larger, overextension of the focal organization's non-scale free R&D resources will considerably hamper knowledge recombination efforts at the project-level.

To translate potential into realized knowledge recombination opportunities when going-together, the focal organization needs to deploy a lot of resources in order effectively identify, retrieve, and recombine partners' external component knowledge. It follows that, if insufficient resources are available in going-together projects, the focal organization will be considerably less able to realize potential recombination opportunities. In support of this notion, numerous KBV studies (e.g. Bos *et al.,* 2017; Deeds & Hill, 1996; Laursen & Salter, 2006) show that organizations should concentrate R&D resources, rather than spread them too broadly, in order to benefit from extramural knowledge recombination. Taken together, we argue that when the focal organization's R&D project portfolio is larger, this will substantially reduce the realization of potential recombination opportunities in going-together projects, bringing their problem-solving performance closer to that of going-alone projects. Therefore, we formulate the following hypothesis:

H4: The focal organization's challenge-based R&D project portfolio size decreases the positive performance gap between going-together and going-alone

4.3. Methodology

4.3.1. Sample and data collection

Various government-supported programs have been initiated over the past few years in order to address important societal problems such as climate change, demographic changes, and smarter infrastructure (Olsen *et al.,* 2016). Government institutions generally issue calls for these programs, soliciting organizations to apply for various research projects that are targeted towards specific (technological) problems. These programs have the potential to make a big impact, as they allow coordinating and orchestrating various R&D efforts on a large scale. Indeed, in these programs, government institutions can align concerted R&D efforts by various parties with one another towards one common objective, potentially increasing the success rate of solving extant societal problems.

In this study, we specifically looked at challenge-based R&D projects that are part of the U.S. Department of Energy's (DOE) *Hydrogen and Fuel Cells Program* (HFCP hereafter)[2]. Hydrogen and fuel cell technologies form an increasingly prominent part of the United States' strategy to advance clean energy technologies and increase energy independence from oil. Fuel cell and associated hydrogen technologies are still in the early stage of commercialization, with numerous technical issues that still need to be addressed. Since the technology remains vastly uncommercialized, concerted government support is required in order to move the technology into the commercialization stage. The projects within this program tackle major issues hampering broad-scale fuel cell technology commercialization[3]. Hence, projects within this program are problem-oriented, as they are designed in

[2] The program was referred to as the Hydrogen, Fuel Cells, & Infrastructure Technologies Program between 2002-2009, the Fuel Cell Technologies Program between 2009 and 2012, and the Hydrogen and Fuel Cells Program since 2012.

[3] These (non-)technological issues are determined based upon, among other things, past programs' outputs as well as the advice of numerous national and international experts.

such a way that particular (technological) targets are met before a certain point in time. For instance, two of the 2020 technological targets set by the DOE for fuel cell power systems are (i) to increase their durability to 5,000 hours and (ii) decrease their cost efficiency to below 40$/kW (Satyapal, 2017). Hence, various projects within the fuel cell section of the HFCP focus on improving the durability and costs of fuel cell system components. Thus far, with an average annual budget of c.a. 180$mn, this program has contributed to important progress in fuel cell and hydrogen technologies, reducing the costs of fuel cell systems, increasing the durability of fuel cell stacks, increasing the mass density of hydrogen storage tanks, and generating ample patented inventions, commercial products, and new job opportunities (PNNL, 2017; Satyapal, 2017).

A unique feature of this data is that we can observe with high reliability the configuration of challenge-based R&D projects, in which focal organizations either go-alone or go-together. Specifically, in these projects, a project leader (i.e. the focal organization) is in charge of coordinating R&D activities, whilst also participating in them, to ensure that project objectives are met at a certain point in time. Importantly, the project leader may also enlist subcontractors in the project, which undertake R&D tasks within the project whilst reporting to the project leader. Using this information, we operationalize the dichotomy between go-together and go-alone by examining whether the project leader involves any subcontractors in the project. To track the configuration of projects over time, we examined project progress reports in the annual HFCP progress reports. All projects that are sponsored by the HFCP have to submit an abstract of the research they conducted during the past fiscal year, summarizing activities and progress made, which is subsequently made available online (https://www.hydrogen.energy.gov/). By inspecting these progress reports, we were able to track every project in this program over a long period of time, capturing the entire population of projects within this single program. The information contained in these abstracts is highly standardized, and could be retrieved for every year between 2003 and 2016. We used these progress reports to infer the identity of the project leader and potential subcontractors, and capture other relevant project-related information, such as the contract number associated with the project.

4.3.2. Variables

Dependent variable. To capture a project's performance, research on interorganizational collaboration often relies on (i) aggregated performance measures, such as an organization's net profit margin (e.g. Jiang, Tao, & Santoro, 2010) or (ii) project-level performance measures derived from surveys (e.g. Lane & Lubatkin, 1998; Cuypers, Ertug, Reuer, & Bensaou, 2017). Despite the merits of these two types of performance measures, they also have some important limitations. Notably, aggregated performance measures, like net profit margin, do not allow to isolate the performance effect of particular projects. Moreover, studies using surveys might suffer from common method bias. As we explain below, we deviate from these prior studies by using a performance indicator that is (i) measured at the project-level, providing a direct connection between the project's inputs and outputs, (ii) highly objective, because it is derived from anonymous peer reviewers with no conflicts of interest, and (iii) highly standardized across different projects.

The project's problem-solving performance data was retrieved from the HFCP Annual Merit Review (AMR) and Peer Evaluation reports, available on the DOE hydrogen website. Each year, the projects supported by the HFCP are evaluated through expert peer review[4] for three main reasons: (i) inform decision-making regarding funding of projects (e.g. should the project be discontinued, receive more/less funding in the following year), (ii) find ways to improve project performance and (iii) refocus program-wide objectives towards more productive ends (EERE, 2016). During the annual AMR meeting, projects are presented during workshops, allowing for peer reviewers to evaluate the project on its merits. Peer reviewers are additionally provided ahead of time with "an advance copy of the project summaries, reviewer instructions, evaluation forms for each project, an agenda, and an overall evaluation package specifically for that reviewer (EERE, 2016, p. 13)". The quality, objectivity and impartiality of reviewers is ensured through (i) only selecting reviewers with relevant experience in the field (based on, e.g. publication record and relevant degrees), (ii) anonymity of peer reviewers, and

[4] We note that not every project was evaluated on a yearly basis. In the EERE peer review guidelines (EERE, 2016), it is mentioned that some projects are excluded from peer evaluation if, for example, they had only very recently started or because they have already been retired.

(iii) not assigning reviewers to projects for which they might have a conflict of interest (EERE, 2016). The peer reviewers are asked to rate each project on a 4-point scale (1 being the lowest and 4 being the highest) along five dimensions: (i) Relevance to overall DOE objectives, (ii) approach to performing the research and development, (iii) technical accomplishments and progress toward project and DOE goals, (iv) technology transfer/collaborations with industry, universities and other laboratories, (v) approach to and relevance of proposed future research[5]. A final score is then derived by taking the weighted average of these five dimensions[6]. The DOE uses these overall project scores as a means to compare projects with each other, determining which projects perform well and which do not within the framework of the program. These evaluations are then collected and summarized in an evaluation report, referred to as the AMR evaluation report. The way in which performance was assessed over the years remained highly stable. The only noteworthy difference was that the weight of each dimension in the total score changed over the years. For example, the dimension related to technological accomplishments and progress received higher weights in later years (20% in 2003, 35% between 2004-2007, 40% between 2008-2012, and 45% between 2009-2016). We controlled for these shifts in importance attributed to different performance dimensions by including year dummies in all models.

Independent variables. To test the first hypothesis, we examined whether the project leader enlisted any subcontractors during the past fiscal year using data from the annual progress reports. If a subcontractor was listed in the project description, the variable *Going-together* took a value of 1, and a value of 0 if this was not the case (i.e. going-alone). To test the second hypothesis, we looked at whether the project leader listed on a project was a firm (=0) or a research organization (=1) (*Research organization*). In the latter category, we included

[5] Some minor variations occur. For example, American Recovery and Reinvestment Act (ARRA) projects were not evaluated for their future research directions. Similarly, technology validation and market transformation projects, in the years 2014-2016, were not evaluated on this dimension. We control for this through the inclusion of program section dummies.

[6] For example, in 2005, a project titled 'Complex Hydride Compounds with Enhanced Hydrogen Storage Capacity', led by United Technologies Research Center (UTRC), received a score of 3.5 for relevance to overall DOE objectives (20%), a 3.5 for approach to performing the research and development (20%), a 2.9 for technical accomplishments and progress toward project and DOE goals (35%), a 3.2 for technology transfer/collaborations with industry, universities and other laboratories (10%), and a 2.9 for approach to and relevance of proposed future relevance (15%), resulting in a final score of: $(3.5*0.2)+(3.5*0.2)+(2.9*0.35)+(3.2*0.1)+(2.9*0.15) = 3.2$.

universities as well as research institutes (Mora-Valentin, Montoro-Sanchez, & Guerras-Martin, 2004). To test the third hypothesis, we measured the project leader's internal knowledge pool size (*Internal knowledge pool size)* by inspecting the number of patents filed by the focal organization as part of projects that were supported by the HFCP (or one of its predecessors)[7]. We were able to identify these patents by examining the 2016 version of the *Pathways to Commercial Success* (PCS) report generated by the Pacific Northwest National Laboratory (PNNL) under contract of the DOE, and released to the public in October 2017 (PNNL, 2017)[8]. This report keeps detailed track of all patents, jobs, and commercial products that are generated resulting from support of the HFCP. It is important to note that only granted USPTO patents are recorded in this report, implying that we capture the size of the internal knowledge pool based on the generation of high-quality technological solutions. To infer when a particular patent was created, we used its priority date, rather than its publication date. To test the fourth hypothesis, we counted the number of concurrent R&D projects in which the project leader is engaged (*R&D project portfolio size)*. Specifically, we measured this variable by counting the number of R&D projects that were evaluated in the current fiscal year in which the focal organization was also involved as a leading entity.

Control variables. We controlled for several relevant project-level characteristics. First, we controlled for the age of the project (*Project age*). Given the learning benefits associated with undertaking problem-solving activities over longer periods of time (Darr *et al.,* 1995), it is expected that projects that have been ongoing for longer periods perform better. To calculate this variable, we subtracted the current year from the year in which the project was initiated (as mentioned on the contract corresponding to the project). We also used a dummy variable to control for whether a project was congressionally directed; that is, if it received funding from a source outside the DOE (C*ongressionally directed project*). The DOE has less influence on funding decisions regarding these projects. Therefore,

[7] The HFCP was initiated in 2002, with first project evaluations provided in 2003 (i.e. the first year in our database). However, before this, various EERE-funded programs targeted towards improving fuel cell and hydrogen technologies were already undertaken. For example, within the Office of Transportation Technologies, the 'Transportation Fuel Cell Power Systems Program' resulted in several patented inventions which were included in the PCS report.

[8] We also verified this information using previous versions of this report that were released on a yearly basis between 2010 and 2016.

project participants have fewer incentives to actually perform well, since poorer performance will not be greatly reflected in the amount of funding the project receives. It is expected that larger projects perform better, given the higher availability of resources to effectuate problem-solving activities. Therefore, we controlled for the size of the project (*Project size*) by looking at the funds allocated to the project by the DOE, as reported by the project participants during the AMR workshops[9]. This variable was divided by 1,000,000 to improve legibility. We controlled for the cost-share percentage of project participants in the project (*Cost share*). In most projects, contracted organizations are required to use some of their own internal funds to support the project. For example, a project led by the company H2Gen Innovations Inc. on improving a hydrogen generation module (HGM), received DOE funds totaling 3,460,000$, with a contractor share of 1,890,000$ (i.e. 35% of total project funds). This variable is expected to positively influence project performance: the higher the contractors' cost-share, the higher their incentives to perform well, given that their own monetary investments are at stake. We included a control variable that takes a value of 1 when the project was discontinued, relying on data from the AMR evaluation report (*Project discontinued)*. We also controlled for the type of award attached to the project. In the sample, there were two broad types of awards: project grants and cooperative agreements. The main difference between the two types of awards is that, with cooperative agreements, government institutions are more involved in guiding and aiding R&D activities than with project grants. To control for this, we included a dummy variable that takes a value of 1 when the project is a cooperative agreement (*Cooperative agreement*). Some projects in the program were part of a hydrogen storage excellence center. Membership in such an excellence center confers various benefits to project participants, such as improved coordination with other projects within the same center, leading to potentially higher problem-solving performance.

[9] This information was validated using data from the U.S. government (available at www.usaspending.gov). To do this, we searched for all contract numbers that were attached to the projects in the HFCP. In case this information was not reported in the annual progress report (which it often was not), we used the Office of Scientific and Technical Information's (OSTI) SciTech Connect database, AMR workshop presentation slides (available on the DOE hydrogen website), or patents and academic publications that were published on the basis of the projects. Next to validating the size of project funds, it was also necessary to obtain contract numbers for each project in order to determine (i) whether a project was a cooperative agreement, project grant, contract, or government laboratory subcontract, (ii) identify which office (within the DOE) funded the project, (iii) and the starting date of the project.

Therefore, we included a dummy variable that takes a value of 1 when a project was part of such an excellence center (*Excellence center*), using information from the annual progress reports.

We further controlled for two relevant characteristics of the focal organization. To capture the go-alone and go-together experience of the focal organization, we counted the number of times (prior to the current year) that the focal organization had been enlisted as a project leader on a project in which no subcontractors were involved (*Going-alone experience*) and in which at least one subcontractor was involved (*Going-together experience*). We counted every project-year, rather than number of unique projects. The reason was that various projects involved subcontractors during a particular phase, but not prior or subsequent ones; hence, numerous projects were not uniquely organized using a going-together or going-alone strategy.

In all models, we further included dummies for (i) the program section within which the project fell (i.e. Hydrogen Storage; Hydrogen Production and Delivery; Fuel Cells; Systems Analysis; Safety, Codes, and Standards; Market Transformation; Technology Validation; American Recovery and Reinvestment Act; Manufacturing R&D), (ii) years (i.e. 2003-2016), (iii) the state-of-residence of the project leader, to control for geographical factors influencing problem-solving performance, and (iv) the office within the DOE from which funding was provided (i.e. although the majority of project funding comes from Office of Energy Efficiency and Renewable Energy (EERE), small contributions are also made by other offices such as the Office of Fossil Energy, the Office of Nuclear Energy, and the Office of Science).

4.3.3. Analytical method

The unit of analysis in this study is the project-year (e.g. a project that is evaluated three times, represents three separate observations). The full sample includes 1082 project-years spread across 414 unique R&D projects[10]. Despite the fact that the

[10] In our sampling strategy, we excluded challenge-based R&D projects which (i) were not led by a firm or research organization, (ii) fall within the 'education' section of the HFCP and therefore do not involve R&D activities, (iii) had not been ongoing sufficiently long enough to have been evaluated along all relevant dimensions (i.e. certain projects were already evaluated before achieving any substantial technological progress), (iv) only coordinated smaller sub-projects (e.g. EMTEC, through an award by the DOE, coordinated several smaller sub-projects, but did not take part in them), or (v) were supported through a contract or government laboratory subcontract, rather than an award from the DOE.

dependent variable is lower- and upper-bounded (between 1 and 4), we used an OLS regression method in order to test our hypotheses. Most of the values of the dependent variable are not cornered in the lower or upper bound of the data, and are normally distributed around the mean. This reduced the need to employ more complex non-linear regression methods, such as tobit. Moreover, results are easier to interpret using OLS regressions, given the more straightforward interpretation of regression coefficients (Wiersema & Bowen, 2009). To control for non-independence across observations from the same project, we clustered standard errors at the project level.

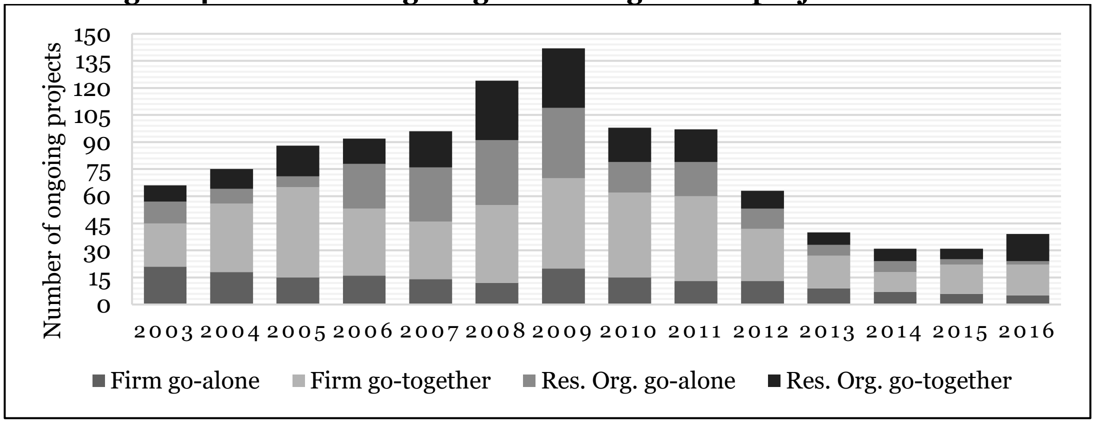
4.3.4. Results

Descriptive statistics. Table 4.1 presents the descriptive statistics and correlation matrix. In our sample, in most project-years (62.66%), the focal organization is going-together. We also observe that going-together is relatively more prevalent amongst firms (71.38% of project-years) compared to research organizations (49.89% of project-years). We plot these trends in Figure 4.1. The dependent variable, problem-solving performance, is normally distributed with a mean of 2.99, a standard deviation of 0.39, a minimum of 1.4, and a maximum of 3.8. The average internal knowledge pool has a size of 3.39. Moreover, in the average project-year, the project leader is involved in 1.71 concurrent R&D projects. Finally, the correlation matrix shows no evidence of multicollinearity. VIF analyses, based on OLS regression, support this, returning average (1.28) and maximum (1.56) values that are far below the advised threshold value of 10 (Mason & Perrault, 1991).

Table 4.1. Descriptive statistics and correlation matrix

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Problem-solving performance	1													
2	Go-together	0.08	1												
3	Research organization	0.10	0.02	1											
4	Internal knowledge pool size	0.21	0.14	0.30	1										
5	R&D project portfolio size	-0.32	0.07	-0.06	-0.05	1									
6	Project age	0.09	0.04	0.06	0.15	-0.09	1								
7	Cost share	-0.35	-0.09	-0.01	-0.05	-0.03	-0.16	1							
8	Project size	0.06	-0.02	-0.12	-0.11	-0.09	0.33	-0.13	1						
9	Project discontinued	0.12	0.35	-0.03	-0.08	0.00	0.09	-0.09	0.08	1					
10	Cooperative agreement	0.13	0.14	0.06	0.04	0.04	-0.05	-0.09	-0.06	0.35	1				
11	Congressionally directed project	-0.17	0.05	-0.27	-0.21	0.05	-0.04	0.16	0.21	0.07	-0.17	1			
12	Excellence center	0.16	0.07	0.15	0.23	-0.02	0.01	-0.08	-0.01	0.31	0.38	-0.21	1		
13	Go-alone experience	0.08	0.01	0.01	-0.02	-0.06	0.10	-0.04	-0.01	0.26	0.27	-0.11	0.28	1	
14	Go-together experience	0.07	-0.14	0.09	0.15	0.05	-0.09	0.01	-0.33	-0.22	0.19	-0.22	0.09	-0.02	1
	Mean	2.99	0.63	0.41	3.39	1.71	2.65	0.26	3.44	0.07	0.52	0.10	0.13	1.73	3.29
	SD	0.39	0.48	0.49	7.63	1.14	1.57	0.14	6.48	0.25	0.50	0.30	0.33	2.93	4.92
	Min	1.40	0	0	0	1	0	0	0.07	0	0	0	0	0	0
	Max	3.80	1	1	45	8	10	0.76	44.4	1	1	1	1	16	28

Figure 4.1. Number of go-together and go-alone projects over time



Regression results. In Table 4.2 we present the regression results. Projects that receive more funding tend to perform better (Model 1: $\beta_{\text{Project size}} = 0.009$, $p < 0.001$). Moreover, projects that were subsequently discontinued tend to perform worse (Model 1: $\beta_{\text{Project discontinued}} = -0.445$, $p < 0.001$). Congressionally-directed projects also tend to perform worse (Model 1: $\beta_{\text{Congressionally directed project}} = 0.401$, $p < 0.001$). In line with our expectations, being part of an excellence center leads to higher problem-solving performance (Model 1: $\beta_{\text{Excellence center}} = 0.163$, $p < 0.01$). The going-together experience of the focal organization has a negative influence on problem-solving performance (Model 1: $\beta_{\text{Go-together experience}} = -0.008$, $p < 0.05$), while going-alone experience does not statistically significantly influence problem-solving performance. Notably, the project leader's internal knowledge pool size has a positive but only marginally statistically significant influence on problem-solving performance (Model 1: $\beta_{\text{Internal knowledge pool size}} = 0.004$, $p < 0.1$).

In Model 2, we test Hypothesis 1. We find that going-together has a positive and marginally statistically significant influence on problem-solving performance (Model 2: $\beta_{\text{Go-together}} = 0.055$, $p < 0.1$), supporting Hypothesis 1. Moreover, testing Hypothesis 2, we find a marginally statistically significant and negative interaction between going-together and research organization-led projects (Model 3: $\beta_{\text{Go-together} \times \text{Research organization}} = -0.103$, $p < 0.1$). However, since the coefficient for the interaction only tells us that the overall interaction effect is statistically significant, we also computed partial effects and found that (i) firms that go-together have significantly higher problem-solving performance than firms that go-alone ($\frac{dy}{dx} = 0.099$, $p<0.01$) and (ii) research organizations that go-together do not have statistically higher or lower problem-solving performance than research organizations that go-alone (see Figure 4.2).

For Hypothesis 3, we find a positive and statistically significant interaction between going-together and the focal organization's internal knowledge pool size (Model 4: $\beta_{\text{Go-together} \times \text{Internal knowledge pool size}} = 0.008$, $p < 0.05$) (see Figure 4.3). To properly test Hypothesis 3, we test the difference in problem-solving performance between going-together and going-alone for different values of the focal organization's internal knowledge pool size (i.e. the difference between the dashed and solid line in Figure 4.3). We find that within a reasonable range ([4,45]) of values of internal knowledge pool size (i.e. 21.5% of the sample), the difference between going-together and going-alone is positive and statistically significant ($p < 0.05$), supporting Hypothesis 3.

Finally, we find a statistically non-significant interaction between the focal organization's R&D project portfolio size and going-together for Hypothesis 4. However, when testing whether this relationship is instead driven by curvilinear effects in model 7, we indeed find a statistically significant interaction (Model 7: $\beta_{\text{Go-together} \times \text{R\&D project portfolio size}} = 0.136$, $p < 0.05$; $\beta_{\text{Go-together} \times \text{R\&D project portfolio size squared}} = -0.022$, $p < 0.01$). This relationship is plotted in Figure 4.4. Subsequently, we computed partial effects to test the difference in problem-solving performance between going-together and going-alone at different values of R&D project portfolio size: (i) when the focal organization is engaged in one project, there is no statistical difference in problem-solving performance between going-together and going-alone, (ii) when the focal organization has 2 or 3 concurrent projects, there is a positive and statistically significant difference in problem-solving performance between going-together and going-alone ($p < 0.05$), (iii) when the focal organization has 4-7 concurrent projects, there is no statistically significant difference in problem-solving performance between going-together and going-alone, and (iv) when the focal organization has 8 projects, going-together performs statistically significantly worse than going-alone ($p < 0.05$). Thus, we find that (i) there seem to be benefits associated with a larger R&D project portfolio and (ii) there are indeed liabilities associated with a larger R&D project portfolio, but these only emerge when the R&D project portfolio is very large. Hence, we find partial support for Hypothesis 4.

Figure 4.2. Firm and research organization go-together performance

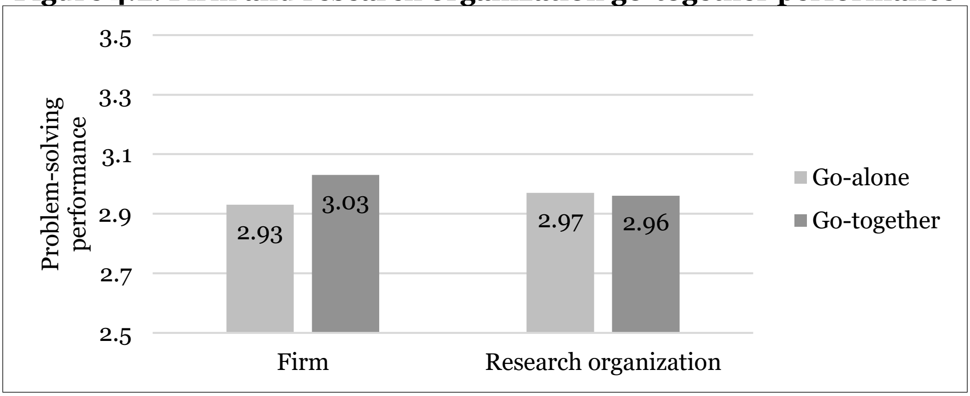


Figure 4.3. Interaction go-together and internal knowledge pool size

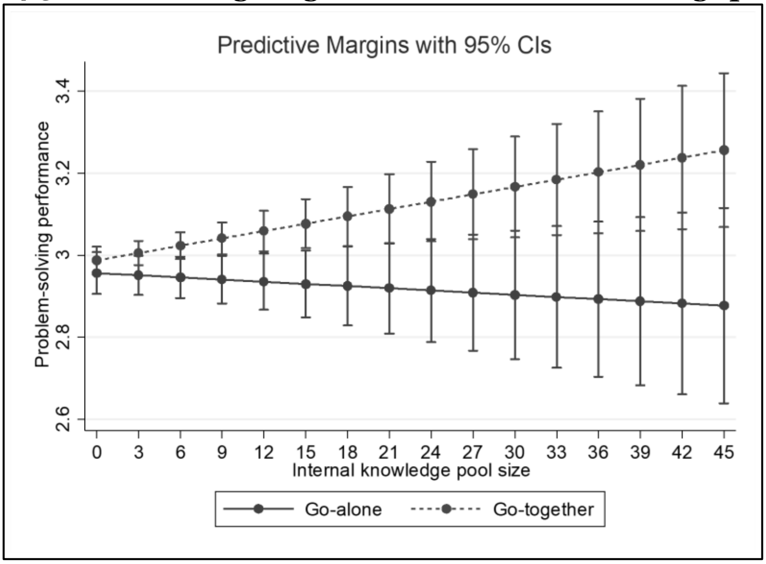


Figure 4.4. Interaction go-together and R&D project portfolio size

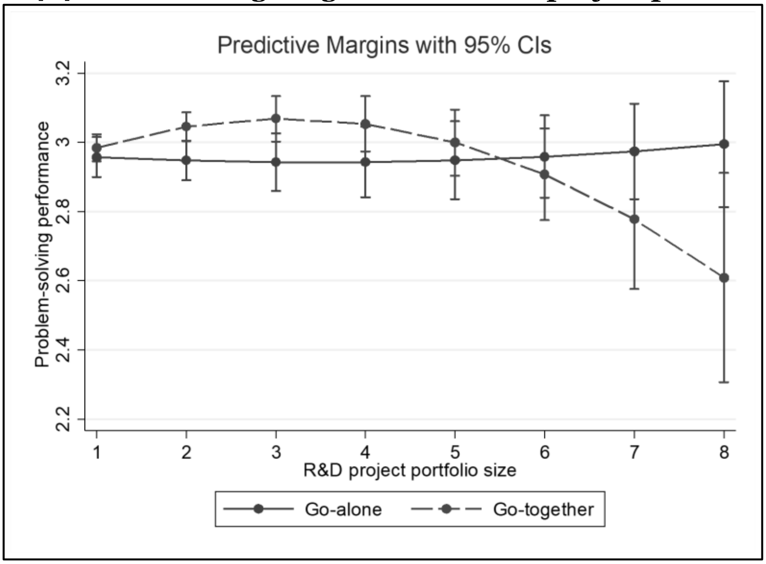


Table 4.2. Pooled OLS regression results

DV: Problem-solving performance	1	2	3	4	5	6	7	8
Project age	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]
Cost share	0.09	0.09	0.08	0.09	0.09	0.09	0.08	0.06
	[0.13]	[0.13]	[0.13]	[0.13]	[0.13]	[0.12]	[0.13]	[0.12]
Project size	0.01***	0.01***	0.01***	0.01***	0.01***	0.01***	0.01***	0.01***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Project discontinued	-0.45***	-0.45***	-0.44***	-0.44***	-0.45***	-0.44***	-0.43***	-0.43***
	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]
Cooperative agreement	0.01	0.01	0.01	-0.00	0.01	0.01	0.01	0.00
	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]	[0.04]
Congressionally directed project	-0.40***	-0.40***	-0.39***	-0.40***	-0.40***	-0.40***	-0.40***	-0.40***
	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]
Excellence center	0.16**	0.19**	0.18**	0.20**	0.18**	0.18**	0.18**	0.19**
	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]	[0.06]
Go-alone experience	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]
Go-together experience	-0.01*	-0.01*	-0.01*	-0.01*	-0.01*	-0.01**	-0.01**	-0.01**
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Research organization	-0.03	-0.02	0.03	-0.03	-0.02	-0.03	-0.03	0.02
	[0.04]	[0.04]	[0.06]	[0.04]	[0.04]	[0.04]	[0.04]	[0.06]
Internal knowledge pool size	0.00†	0.00†	0.00	-0.00	0.00†	0.00†	0.00†	-0.00
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
R&D project portfolio size	0.00	0.00	0.00	0.01	0.00	0.06	-0.02	0.00
	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.04]	[0.04]	[0.05]
Go-together		0.06†	0.10**	0.03	0.05	0.06	-0.09	-0.03
		[0.03]	[0.04]	[0.03]	[0.05]	[0.05]	[0.08]	[0.08]
Go-together × Research organization			-0.10†					-0.10
			[0.06]					[0.06]
Go-together × Internal knowledge pool size				0.01*				0.01†
				[0.00]				[0.00]
Go-together × R&D project portfolio size					0.00	-0.00	0.14*	0.11†
					[0.02]	[0.02]	[0.06]	[0.06]
R&D project portfolio size squared						-0.01	0.00	0.00
						[0.00]	[0.01]	[0.01]
Go-together × R&D project portfolio size squared							-0.02**	-0.02*
							[0.01]	[0.01]
Fiscal year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State-of-residence dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HFCP section dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DOE office dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1082	1082	1082	1082	1082	1082	1082	1082
R^2	0.42	0.43	0.43	0.43	0.43	0.43	0.43	0.44
Adjusted R^2	0.38	0.38	0.38	0.38	0.38	0.38	0.39	0.39

† p < .10, * p < .05, ** p < .01, *** p < .001. Standard errors clustered at project-level between brackets.

Robustness checks. We conduct several robustness checks in order to verify the stability of our findings. First, we reestimate our models using tobit regressions, and find highly stable results. Second, in Table 4.3, we split the sample up into (i) a group which only contains firm-led R&D projects, (ii) a group which only contains research organization-led R&D projects, (iii) a group which only contains R&D projects in which the focal organization is going-alone, and (iv) a group which only contains R&D projects in which the focal organization is going-together. Across all subsamples, we find results that confirm our main results. Third, we exclude projects in which the focal organization is a research institute, focusing solely on the difference in problem-solving performance between universities and firms. Results remain very similar. Fourth, we rerun the analyses including challenge-based projects that (i) fall within the 'education' section of the HFCP, (ii) are supported via a contract or a government laboratory subcontract, (iii) have not been ongoing long enough to be evaluated along all performance dimensions, and (iv) coordinated smaller sub-projects (see footnote 10), leaving the main results largely unchanged. Fifth, winsorizing at the 1st and 99th percentile the dependent variable and the independent variables capturing the focal organization's internal knowledge pool size and R&D project portfolio size, result remain stable.

Table 4.3. Subsample robustness checks

	Firm		Res. org.		Go-alone					Go-together				
DV: Problem-solving performance	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Project age	0.00	0.01	0.01	0.01	-0.00	-0.01	-0.01	-0.01	-0.01	-0.00	0.00	0.00	0.00	0.01
	[0.01]	[0.01]	[0.02]	[0.02]	[0.02]	[0.02]	[0.02]	[0.02]	[0.02]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]
Cost share	0.14	0.15	-0.25	-0.24	0.08	0.16	0.17	0.17	0.17	0.33*	0.19	0.21	0.21	0.17
	[0.15]	[0.15]	[0.38]	[0.38]	[0.21]	[0.21]	[0.21]	[0.21]	[0.21]	[0.16]	[0.16]	[0.15]	[0.15]	[0.15]
Project size	0.01***	0.01***	0.02	0.02	0.01	0.01	0.01†	0.01†	0.01†	0.01***	0.01***	0.01*	0.01*	0.01*
	[0.00]	[0.00]	[0.02]	[0.02]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Project discontinued	-0.42***	-0.41***	-0.49***	-0.49***	-0.61***	-0.61***	-0.61***	-0.61***	-0.61***	-0.39***	-0.39***	-0.37***	-0.37***	-0.36***
	[0.07]	[0.07]	[0.05]	[0.05]	[0.07]	[0.07]	[0.07]	[0.07]	[0.07]	[0.05]	[0.06]	[0.05]	[0.05]	[0.05]
Cooperative agreement	0.04	0.03	-0.03	-0.03	0.03	0.03	0.02	0.02	0.02	-0.03	-0.03	-0.03	-0.03	-0.04
	[0.05]	[0.05]	[0.08]	[0.08]	[0.07]	[0.07]	[0.08]	[0.08]	[0.08]	[0.05]	[0.05]	[0.05]	[0.05]	[0.05]
Congressionally directed project	-0.34***	-0.33***	-0.47***	-0.47***	-0.53***	-0.53***	-0.53***	-0.54***	-0.54***	-0.38***	-0.37***	-0.37***	-0.37***	-0.38***
	[0.10]	[0.09]	[0.10]	[0.10]	[0.13]	[0.13]	[0.13]	[0.13]	[0.13]	[0.08]	[0.07]	[0.07]	[0.07]	[0.07]
Excellence center	0.09	0.13	0.15	0.15	0.03	0.02	0.03	0.03	0.03	0.29***	0.30***	0.29***	0.29***	0.29***
	[0.08]	[0.08]	[0.10]	[0.10]	[0.08]	[0.08]	[0.09]	[0.09]	[0.09]	[0.08]	[0.08]	[0.08]	[0.08]	[0.08]
Go-alone experience	0.01	0.01	-0.01	-0.01	-0.00	-0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
	[0.01]	[0.01]	[0.02]	[0.02]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]
Go-together experience	-0.01*	-0.01*	-0.02†	-0.02†	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01†	-0.01*	-0.01*	-0.01**
	[0.00]	[0.00]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Go-together		0.10**		-0.02										
		[0.04]		[0.06]										
Research organization						0.09	0.09	0.09	0.09		-0.13**	-0.11*	-0.11*	-0.13**
						[0.08]	[0.08]	[0.08]	[0.08]		[0.04]	[0.04]	[0.04]	[0.04]
Internal knowledge pool size	0.00	0.00	0.01	0.01			-0.00	-0.00	-0.00			0.01**	0.01**	0.01**
	[0.00]	[0.00]	[0.01]	[0.01]			[0.00]	[0.00]	[0.00]			[0.00]	[0.00]	[0.00]
R&D project portfolio size	0.00	0.00	-0.00	-0.00				-0.00	0.00				-0.00	0.11*
	[0.01]	[0.01]	[0.04]	[0.04]				[0.02]	[0.05]				[0.02]	[0.05]
R&D project portfolio size squared									-0.00					-0.02**
									[0.01]					[0.01]
Fiscal year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State-of-residence dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HFCP section dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DOE office dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	643	643	439	439	404	404	404	404	404	678	678	678	678	678
R^2	0.42	0.43	0.50	0.50	0.51	0.51	0.51	0.51	0.51	0.45	0.46	0.47	0.47	0.48
Adjusted R^2	0.35	0.36	0.41	0.41	0.42	0.42	0.42	0.42	0.42	0.38	0.39	0.41	0.40	0.41

† $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$. Standard errors clustered at project-level between brackets.

4.4. Discussion and conclusion

Using data regarding 414 challenge-based R&D projects over a 14-year time-period (2003-2016), we examined the difference in problem-solving performance between going-together and going-alone. The findings indicate that (i) there is a marginally significant positive effect of going-together on problem-solving performance, (ii) there is a positive problem-solving performance gap between going-together and going-alone for firms but not for research organizations, (iii) the larger the focal organizations' internal knowledge pool, the larger the positive problem-solving performance gap between going-together and going-alone, and (iv) the focal organization's R&D project portfolio size initially increases the positive problem-solving performance gap between going-together and going-alone but, beyond a certain point, decreases it. These findings have important theoretical and practical contributions, which we discuss in the next section.

4.4.1. Theoretical implications for grand challenges literature

In this study, we deviated from prior grand challenges and open innovation studies, by relaxing the implicit assumption that going-together always outperforms going-alone in terms of generating high-quality solutions. We argued that not every organization is able to reap the unique knowledge recombination benefits of going-together to the same extent, since this problem-solving approach requires abilities to identify, retrieve and recombine component knowledge across organizational boundaries. Based on this, we argued that there are three characteristics of the focal organization that influence these abilities.

Focal organization's institutional background. We expected that, for research organizations, owing to their institutional mission of creating and diffusing new technological knowledge, the positive performance gap between going-together and going-alone would be larger than for firms. However, these expectations were not confirmed: we, instead, found strong evidence that firms are better able to reap the relative benefits of going-together compared to going-alone than research organizations. Perhaps this unexpected finding can be explained by the fact that firms are actually better at managing interorganizational partnerships than research organizations. Specifically, firms tend to govern and coordinate activities through active and frequent monitoring (Williamson, 1991), so as to ensure that their short-term goals can be met and that no delays are incurred (Cyert & Goodman, 1997). As such, it is likely that firms, as leading entities, regularly check up on partners to verify that they are doing what they are supposed to do within the framework of the project (Das, 2005). This implies that, when they go-together, firms will pay considerable attention to whether the partners' problem-solving activities are conducive to achieving the intended technological objectives, typically improving overall problem-solving performance (e.g. Sampson, 2007). In contrast, since research organizations tend to emphasize collegiality and democracy in governing activities (Manning, 2013), they might generally take a more laissez-faire attitude towards the problem-solving activities of external partners, being less attentive to whether they actually contribute to achieving the project's technological goals. This will, in turn, reduce the focal organization's ability to benefit substantially from going-together relative to going-alone.

This study contributes to the literature on challenge-based R&D project and open innovation in two ways. First, we contribute to these literatures by emphasizing the importance of partner management capabilities (Ireland, Hitt, & Vaidyanath, 2002; Majchrzak, Jarvenpaa, & Bagherzadeh, 2015). Our findings suggest that, despite the overall openness of research organizations towards external knowledge (Trajtenberg *et al.,* 1997), it is also pertinent that they, as leading entities, have the ability to manage interorganizational partnerships effectively. Otherwise, as our findings suggest, the collaborative knowledge recombination benefits of going-together will not be reaped. In contrast, our findings show a rather large difference in problem-solving performance between firms that go-together and those that go-alone. These findings suggest that firms have an advantage as leading entities in collaborative challenge-based R&D projects, possibly due to their superior ability to manage partners effectively, monitoring their activities and aligning them towards a common technological objective (Das, 2005). Second, we contribute to these literature streams by showing that there are important differences in problem-solving performance patterns between firms and research organizations. In particular, extant literature has principally focused on the firm as the focal actor, neglecting the important role of research organizations in engendering technological change. This is surprising, given the sheer number of challenge-based R&D projects that are undertaken by research organizations (i.e. 40% of project-years in our sample). Our findings show that this distinction is highly relevant, as the two types of organizations seem to engage in problem-solving activities rather differently. We therefore encourage future studies to consider the dichotomy between firms and research organizations more extensively in their conceptual and empirical framework.

The benefits of a large internal knowledge pool. As predicted, we found strong evidence to suggest that, the larger the focal organization's internal knowledge pool, the better its ability to translate potential into realized knowledge recombination opportunities when going-together (Zahra & George, 2002). This reflects an experience effect – i.e. organizations with larger internal knowledge pools have more experience identifying valuable component knowledge for recombination (Cohen & Levinthal, 1990) – and a retrieval effect – i.e. organizations with larger internal knowledge pools can more easily communicate with external partners, transferring component knowledge across organizational boundaries (Lane & Lubatkin, 1998; Mowery *et al.,* 1996; Sampson, 2007).

At the same time, we note that, in our sample, going-together only outperforms going-alone, in terms of problem-solving performance, when the focal organization has previously generated more than three unique high-quality solutions. This suggests that there are some boundary conditions to benefiting from prior technological experience (Argote & Miron-Spektor, 2011; Garud & Nayyar, 1994; Hargadon & Sutton, 1997). Recently, this discussion has reemerged, with studies questioning the benefits of prior technological experience (e.g. Anand, Mulotte, & Ren, 2016), especially in the context of knowledge recombination (e.g. Ghosh *et al.,* 2014). Contributing to this ongoing discussion, our findings suggest that organizations need to 'learn to learn' (Levinthal & March, 1993), pinpointing how the generation of new technological solutions can be leveraged as an asset to improve subsequent problem-solving activities. Thus, to optimally reap the benefits of a going-together problem-solving approach, it is pertinent that focal organizations have considerable experience generating high-quality solutions. In this way, extant technological problems can most adequately be addressed.

Benefits and liabilities of large R&D project portfolios. We expected that the positive performance gap between going-together and going-alone would decrease when the focal organization's R&D project portfolio becomes larger, as this would diminish the availability of non-scale free R&D resources required to benefit from going-together at the project-level (Levinthal & Wu, 2010). However, instead of these hypothesized liabilities, we found that there are initially benefits associated with a larger R&D project portfolio, in terms of increasing the problem-solving performance gap between going-together and going-alone. One explanation for this is that concurrent challenge-based R&D projects present alternative sources of information which can be tapped into in order to validate information or resolve uncertainties in other projects (Hargadon & Sutton, 1997; Henderson & Cockburn, 1996). When the challenge-based R&D project portfolio is larger, information pertaining to external components can be cross-validated with individuals involved in other projects, substantially alleviating ambiguities regarding the use of these components in new recombination efforts. In a way, therefore, concurrent challenge-based R&D projects can augment the absorptive capacity of the focal organization, allowing it to benefit more fully from going-together at the project-level. We do note, however, that when the R&D project portfolio is very large, resource constraints that hamper the realization of collaborative knowledge recombination opportunities do seem to emerge, substantially reducing the problem-solving performance gap between going-together and going-alone.

These findings suggest that the performance of single projects may be highly interlinked with that of other projects within the same organization. Hence, the focal organization should carefully consider how newly-engaged challenge-based R&D projects fit within the existing portfolio of projects, such that resource constraints are minimally experienced, and cross-validation benefits are maximally present. To achieve this, our findings suggest that focal organizations should have an intermediate number of concurrent challenge-based R&D projects, in line with what prior studies have found regarding the optimal size of alliance portfolios (Deeds & Hill, 1996; Wassmer, 2010).

4.4.2. Practical implications

Our findings have important policy implications for the configuration of challenge-based R&D projects for solving grand societal challenges. Whereas organizations are often encouraged to organize these challenge-based R&D projects in a collaborative way (Estrada, Faems, Cruz, & Santana, 2016; Olsen *et al.,* 2016), we find evidence to suggest that this is not necessarily conducive to higher problem-solving performance. In particular, although going-together increases the potential for valuable knowledge recombination, not every organization has the ability to fully realize these potential opportunities. Hence, we encourage policy-makers to more carefully design grand challenges programs, such that focal organizations that engage in challenge-based R&D projects employ problem-solving approaches which they are most befit to carry out (e.g. firms, per our findings, should preferably go-together rather than go-alone).

4.4.3. Limitations and future research

This study has several limitations which can serve as interesting starting points for future research. First, we used data on government-supported challenge-based R&D projects in order to examine the performance implications of going-alone and going-together. This setting was ideal for testing our hypotheses, as organizations can opt to go-alone or go-together within comparable R&D projects. Moreover, the distribution of go-alone and go-together projects was very equal in our sample. However, given the specificities of this setting, in terms of the types of problems to be solved, it is necessary that future research replicates our findings in other settings.

Second, we focused solely on the performance implications of going-together and going-alone, but we did not consider the antecedents for choosing either approach to organize challenge-based R&D projects (since this would fall outside the scope of this study). Future research should explore this topic, examining whether certain types of focal organizations are more inclined to opt for a go-together approach, or whether this is dependent on other factors, such as the availability of partners in geographical proximity (Phene & Tallman, 2014).