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Effects of prior knowledge and collaborations on R&D performance in times of urgency: the case of COVID-19 vaccine development

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Innovation usually requires time-consuming exploratory approaches. However, external shocks and related crises, such as the COVID-19 pandemic, lead to severe time pressures, which require short-term R&D results. We investigate how organizations' prior collaboration and existing knowledge not only helped them cope with the crisis but also affected the vaccine's development performance. Specifically, we investigate the R&D outcomes of 386 organizations involved in the COVID-19 vaccine's development within the first 18 months after the pandemic's outbreak. The results reveal that under urgency, organizations with prior scientific collaborations and technological knowledge exhibit a higher R&D performance. Furthermore, a broad network of diverse collaborators strengthened this relationship, thereby calling for more interdisciplinary R&D activities. We therefore extend the literature on innovation speed and strengthen long-term R&D outcomes' role in organizations with a broad existing knowledge base and collaboration networks. We do so by specifically supporting such organizations' ability to integrate their previous R&D's and collaborations' knowledge to achieve rapid innovative outcomes under urgency.

1. Introduction

Crises, such as the COVID-19 pandemic, confront the medical industry with the need to accelerate medical treatments' and vaccines' development. There was roughly a year between the pandemic's outbreak and the start of mass vaccination (Food and Drug Administration, 2020). Never before had the world witnessed as many medical approvals in such a short time. All the successfully authorized COVID-19 vaccines in the United States, such as the Pfizer/Biontech vaccination, were the result of inter-organizational collaborations (Milken Institute, 2022). Whereas innovation usually requires time-consuming exploratory approaches, urgent times induce organizations to promptly utilize their existing resources for immediate action. In this study, we combine literature

© 2024 The Authors. *R&D Management* published by RADMA and John Wiley & Sons Ltd. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made. from two decisive resources that ensure a competitive advantage: time and knowledge. Based on innovation speed's and the knowledge-based view's (KBV) literature, we, therefore, investigate organizations' required internal and external knowledge, and R&D performance effect, using the vaccine development during the COVID-19 pandemic as an example.

Innovation management literature is rich in qualitative comparisons of leading firms' developed technologies (Calvo Fernández and Zhu, 2021), organizational characteristics, collaboration (Bertello et al., 2022; Geurts et al., 2022; Patrucco et al., 2022), and funding activity (Kiszewski et al., 2021; Vermicelli et al., 2021) regarding the COVID-19 vaccine's development. This research finds that coordinating collaboration initiatives' knowledge and exchanging resources increase their learning potential and accelerate their innovation process in times of crisis. In addition, other studies on the COVID-19 vaccine's development focus on the successful acceleration factors (Defendi et al., 2022; Gnekpe et al., 2023). Cooper (2021) discusses the COVID-19 pandemic's lessons learned regarding accelerating the innovation process. He suggests that new-product projects should be adequately resourced using focused project teams, effective portfolio management, digital tools' utilization, and lean and agile development to remove waste and inefficiencies. Nevertheless, the existing literature mainly comprises case studies, which means their findings are hardly generalizable. In addition, efforts to accelerate innovation speed lack a perspective on organizations' knowledge base and collaboration experience.

In this empirical quantitative study, we consider organizations' prior activity regarding their current R&D performance under urgency. We discuss the prior internal and external knowledge that is relevant to the pharmaceutical product development's success. By doing so, our study contributes to the innovation management literature that connects the focal organization's acquired knowledge within its specific collaborating environment when there is a lack of time to do so. We find that knowledge retained from prior R&D experiences is a specifically important internal resource for utilizing new knowledge. Furthermore, prior scientific and technological collaboration networks are critical at such time, since new formal and informal ties cannot be developed as quickly. Transdisciplinary collaborations with partners from different institution types become particularly important if organizations have sufficient prior scientific and technological knowledge. Our study therefore supports the discussion on R&D activities' long-term effects.

This study is structured as follows: We first discuss prior literature on innovation speed during crises and highlight the importance of organizations' previously acquired knowledge and collaboration. Thereafter, we characterize the research-intensive pharmaceutical industry and the COVID-19 pandemic's specific case. With evidence from the literature and qualitative insights into successful COVID-19 vaccine projects, we derive our hypotheses, which we test with logistic regression models from 386 organizations active in COVID-19 R&D. Finally, we discuss our findings and shed light on their theoretical and practical implications.

2. Theoretical background

In dynamic, high-technology industries, such as the pharmaceutical industry, organizations face changing environments with intense competition and perpetually changing technologies (Deeds et al., 2000) as well as market needs (Andrews and Farris, 1972; Brem and Voigt, 2009). Novel circumstances create a new market need to encourage fast product solutions (Bryan et al., 2020). Resources must be especially rapidly activated under urgency to respond to new demands to transform knowledge into innovative products' technological improvements. To do so, organizations require dynamic capabilities that can extend or modify their existing resources (Winter, 2003; Dyduch et al., 2021). Among others, resource reconfiguration depends on creating alliances, on the ability to continuously transform knowledge into new products, and on the ability to effectively absorb, master, and improve existing technologies. As such, differences in resources and capabilities result in organizations' diverging innovation speed (Barney, 1991; Teece et al., 1997; Chen et al., 2010; Ellwood et al., 2017; Cooper, 2021). In this section, we introduce urgency as a trigger of innovation and elaborate on the relevance of an organization's existing innovation abilities regarding grounding R&D rapidly in an organization's dynamic capabilities, particularly about its absorptive capacity.

2.1. Urgency as an R&D driver of immediate resource utilization

New product development speed relates to new product success (Chen et al., 2012). We define *innovation speed* as the time between an innovation's

initial trigger and a new product's commercialization in the market (Kessler and Chakrabarti, 1996). Innovation speed is recognized as creating and sustaining a competitive advantage (Kessler and Chakrabarti, 1996; Chen et al., 2010; Cankurtaran et al., 2013; Ellwood et al., 2017). Kessler and Chakrabarti (1996) mentioned various factors that influence innovation speed. They suggested increasing innovation speed through the external sourcing of specific tasks to consciously limit internal tasks. Among other antecedents, a metaanalysis by Chen et al. (2010) demonstrated empirically that cross-functional teams' use and external partners' involvement in a new product initiative enables accelerated innovation (Chen et al., 2010). In addition, Ellwood et al. (2017) clarified that mechanisms underlying management interventions promote innovation speed.

External crises need coordinated and collected efforts to enable rapid R&D (Chesbrough, 2020). Time pressure does not in itself offer new abilities, but urges organizations to utilize their existing innovation capabilities to accelerate the innovation process. An unexpected external environmental as well as a social or economic shock could trigger a change in organizations' innovative behavior by giving it a solution-oriented focus to immediately mobilize existing resources (Salvato et al., 2020; Aarstad and Kvitastein, 2021; Soluk, 2022). Consequently, urgency uncovers the differences in organizations' innovation abilities.

2.2. Knowledge as a fundamental R&D innovation resource

Permanent heterogeneous strategic innovation resources allow an organization to achieve and sustain its competitive advantage (Barney, 1991; Teece et al., 1997). An organization's knowledge and experience grow with knowledge reuse. Through recombination, existing knowledge is applied to new outcomes (Kogut and Zander, 1992). Nevertheless, knowledge as a crucial innovation resource in dynamic industries (Grant, 1996b; McMillan and Hamilton, 2000; Rothaermel and Hess, 2007) is unlikely to reside within a single organization, thereby requiring formal and informal exchanges with external partners (Powell et al., 1996). Knowledge integration, application, and recombination yield organizational value creation (Cohen and Levinthal, 1990; Grant, 1996a). Newly created or acquired knowledge is retained using organizational routines, which make it available for exploitation in future research (Prabhu et al., 2005; Marsh and Stock, 2006). Inter-organizational collaboration enables joint knowledge integration to co-develop technologies and to exploit innovation (Kogut and Zander, 1992; Grant, 1996b; Chesbrough, 2003). Under urgency, organizations' knowledge utilization dynamics change as time for knowledge acquisition and the formation of new alliances is missing (Reale, 2021).

2.3. Knowledge exchange as an R&D driver

An organization's knowledge base is built on complementary prior scientific and technological knowledge from internal and external sources as contributed by its individuals, organizational learning, and previous R&D experiences (Argote and Miron-Spektor, 2011). Scientific knowledge describes the fundamental science and understanding of a research area. It is oriented toward theoretical constructs' unfolding (Fabrizio, 2009; Watts and Hamilton, 2013). Technological knowledge enables practical solutions, techniques, and concrete applications (Choi, 2019). Despite scientific knowledge's well-known importance as a source of an organization's R&D in the biotechnological and pharmaceutical industry (Kuo et al., 2019), firms tend to instead focus on generating technological knowledge. Conversely, public research institutions focus on basic science rather than on commercial usage (McMillan and Hamilton, 2000), thereby complementing industry as sources of scientific knowledge (Fabrizio, 2009; Melnychuk et al., 2021).

Internal knowledge is found within the organization's R&D process and/or emerges from its experiences (Denicolai et al., 2014). Organizational absorptive capacity is a crucial factor for exploiting internal knowledge effectively and could be developed by means of internal basic research (Fabrizio, 2009). On the other hand, absorptive capacity is defined as a firm's ability to recognize, transform, and exploit external knowledge (Cohen and Levinthal, 1990). By utilizing an organizational learning lens and a knowledge-based view, research underlines absorptive capacity's role as the organization's capability to reconfigure its knowledge foundation, and, therefore, enhancing its sustainable competitive advantage (Lane et al., 2006). Collaboration with external partners provides an organization with access to new, dispersed external knowledge (Grigoriou and Rothaermel, 2017), thereby enhancing its performance and resilience (Ahn et al., 2019). Specifically, collaboration with partners beyond an organization's value chain and international partners has the strongest impact on its performance, as this collaboration increases the chances of acquiring newer knowledge to identify new opportunities to achieve sustainable growth (Ahn et al., 2018). Diverse university-industry collaborations enable knowledge transfers, which increase innovativeness (Melnychuk et al., 2021). Knowledge exchange depends largely on the type of institution.

Organizations engaging in exploiting internal and external knowledge sources improve their innovation capabilities (Kogut and Zander, 1992; Chesbrough, 2003; Cassiman and Veugelers, 2006; Melnychuk et al., 2021). Retained knowledge from prior R&D experiences could be combined with newly acquired or created knowledge for new product development (Marsh and Stock, 2006). In dynamic markets, broad knowledge increases the flexibility to exploit existing resources (Grant, 1996a) and to build, integrate, transform, and mobilize internal and external competences (Teece et al., 1997, 2016). Consequently, absorptive capacity is a decisive organizational capability for transferring knowledge from external sources, especially from universities and public research institutes (Melnychuk et al., 2021). Prior collaborations might support organizational agility, since the knowledge and hands-on experiences gained from such collaborations could be easily transferred and deployed to current value-creating innovation activities (Teece et al., 2016).

3. Hypotheses

We analyze the effects of organizations' prior knowledge and collaboration on their R&D performance. R&D performance is a critical determinant of an organization's productivity and competitive advantage, which accelerate the innovation process (Werner and Souder, 2016). We define an organization's *R&D performance* as the extent to which achieved R&D activities are relevant for bringing a concrete research idea closer to being applied as a potential market exploitation product. The more an organization's product innovation has advanced within the process, the higher the likelihood that it will reach the market promptly.

3.1. Prior internal knowledge and R&D performance resources

Organizations benefit from leveraging internal knowledge for innovation performance (Leiponen and Helfat, 2010; Zhou and Li, 2012), while internal research is a relevant source of new solutions

(Fabrizio, 2009). Under urgency, organizations rely even more on their existing knowledge base. If it exists and is sufficient, organizations utilize prior knowledge rather than investing in their external acquisitions to conduct R&D activities (Ceccagnoli et al., 2010; Caner and Tyler, 2015). Furthermore, the R&D efficiency increases with experience (Yelle, 1979). This might also facilitate organizations' ability to learn from failures to increase their R&D quality (Khanna et al., 2016). The likelihood that organizations will relate to new knowledge is higher if they have a broad existing knowledge base, because this would allow them to better evaluate and utilize potential resources (Cassiman and Veugelers, 2006). A broad knowledge base is a prerequisite for absorptive capacity that offers more opportunities to immediately recombine knowledge. Individuals who repeatedly use their established, specific scientific knowledge develop routines and improve their ability to apply their knowledge in related, future R&D projects (Kuo et al., 2019).

In the pharmaceutical industry, accumulated prior scientific knowledge specifically enhances R&D (Katila and Ahuja, 2002; Marsh and Stock, 2006). The specific knowledge within the therapeutic area provides a basic and a fundamental understanding during the research stage (Xu, 2015; Kuo et al., 2019). Within the pharmaceutical industry, biotechnology firms specifically profit from scientific knowledge's exploitation of basic research to develop breakthrough innovations (Della Malva et al., 2015).

Hypothesis H1 An organization's prior scientific knowledge is positively associated with its R&D performance.

Prior technological knowledge is another important internal resource that created the organizational ability to exploit knowledge for new technical applications. Pharmaceutical firms with an applied science foundation have more new product introductions, suggesting that solutions-based approaches are indicative of an innovative output (Watts and Hamilton, 2013). Technological and product-market experiences in the pharmaceutical industry lead to successful new product introductions (Nerkar and Roberts, 2004). Moreover, prior technological knowledge helps organizations to access resources for future R&D faster (Fabrizio, 2009). Consequently, the absorptive capacity of organizations with a great deal of prior applied knowledge is higher and they are able to provide the pharmaceutical industry with quicker solutions (Fernald et al., 2017). In respect of vaccine and drug development, prior knowledge could also specifically reside within discontinued R&D projects and might even shorten new treatment or vaccine's development process (Harrison, 2016). R&D teams could also re-assess the use of existing drug candidates unsuitable for previous indications (Khanna, 2012). These drug candidates have often already successfully passed several development process stages and exhibit appropriate clinical profiles allowing them to enter the preclinical and the clinical trials directly, thereby decreasing the development costs, risks, and time considerably (Ashburn and Thor, 2004). Organizations owning such drug candidates have advantages, since they could react successfully to urgent innovation needs (Jin and Wong, 2014).

Hypothesis H2 An organization's prior technological knowledge is positively associated with its R&D performance.

3.2. Prior external knowledge and R&D performance resources

External knowledge complements an organization's knowledge base to increase its innovative performance (Caloghirou et al., 2004; Laursen and Salter, 2006). This applies specifically when an organization's internal knowledge base and R&D capabilities are insufficient to generate new knowledge, but the organization does have complementary resources and skills, which shift the focus to external knowledge acquisition (Ceccagnoli et al., 2010; Caner and Tyler, 2015). Under urgency, there is no time to form new partnerships but the existing networks do provide access to multiple sources' external knowledge (Quintana-García and Benavides-Velasco, 2004; Fabrizio, 2009). Existing networks facilitate inter-organizational exchanges, thereby stimulating new R&D collaboration. Organizations could therefore build on formal collaboration guidelines', procedures', and project administrations' processes established during specific previous collaborations. Consequently, the quality of the relationship between organizations, which have previously worked together, is higher (Inkpen and Tsang, 2005).

Groundbreaking innovations frequently require basic research collaboration (Dismukes et al., 2005), particularly in the pharmaceutical industry (Mansfield, 1995). Scientific collaboration, such as the university-industry collaboration regarding preclinical research, improves organizations' required absorptive capacity for their innovation performance (Banerjee and Siebert, 2017; Melnychuk et al., 2021). A larger network of individual scientists from different research institutions provides access to a more sophisticated scientific knowledge base. Consequently, previous connections to scientists enable an organization to rapidly activate the existing ties in order to access the basic science.

Hypothesis H3 An organization's prior scientific collaboration is positively associated with its R&D performance.

Organizations that have previously collaborated on invention activities, have joint IPRs, have developed legal ties, and exhibit mutual respect and trust that they could transfer to their joint future activities (Inkpen and Tsang, 2005). The roles played in the process of discovering drugs are, for example, clearer between technology-driven biotech companies and big pharma companies that increasingly integrate networks (Rafols et al., 2014). Direct collaboration benefits innovative performance (Ahuja, 2000), while joint projects on actual vaccine candidates enable the most direct exchange of applied technological development.

Hypothesis H4 An organization's prior technological collaboration is positively associated with its R&D performance.

3.3. A collaboration network breadth and R&D performance

When organizations whose institution types and knowledge base differ, cooperate on research projects and alliances, this allows them to access complementary knowledge and technologies, which are important sources of innovative performance (Laursen and Salter, 2006; Cassiman et al., 2008; Xu et al., 2013; Fernald et al., 2017; Grigoriou and Rothaermel, 2017). Public institutions prefer to focus on the early research phases (de Vrueh and Crommelin, 2017), while biotechnological entrepreneurs choose to concentrate on the early development stages (Havenaar and Hiscocks, 2012), and large pharmaceutical firms prefer to focus on the late-stage development as they are experienced in manufacturing, distribution, and marketing (Hoang and Rothaermel, 2010). Furthermore, research institutes' and industry's resources complement one another, particularly within the pharmaceutical industry (Melnychuk et al., 2021). Consequently, a diverse setting of different organizational types is required to develop new drug candidates.

Hypothesis H5 A collaboration network breadth is positively associated with R&D performance.

3.4. Interaction effects of collaboration network breadth

A diverse network allows access to its multiple contributors' more heterogenous knowledge and resources, while also offering more opportunities to recombine knowledge in order to enhance the innovative performance (Zheng, 2010; Xu et al., 2019). A broad collaboration network offers more perspectives on recombining the existing scientific knowledge base, thereby enabling the R&D performance. In broad collaboration networks, each contributing organization plays a very specific role, which no other organization can play. Consequently, organizations benefit from strong and established partnerships, since acquiring and sharing knowledge reciprocally, lead to value creation (Del Giudice and Maggioni, 2014; Dayan et al., 2017). Specifically, at sufficiently high levels of absorptive capacity, R&D efforts' and unrelated external knowledge's tight integration enables pharmaceutical firms to exploit knowledge (Fernald et al., 2017). A pharmaceutical company's external sourcing strategy depends on its internal knowledge base (Gnekpe et al., 2023). On the one hand, an exchange with diverse partners requires network organizations to already have a sufficient knowledge base on which to build. On the other hand, a network organization with prior knowledge could better exploit its collaboration partners' inputs to its own advantage, if these partners could rely on the public's and private actors' support.

Hypothesis H6a An organization's collaboration network breadth interacts positively with its prior scientific knowledge in terms of its effect on the R&D performance.

Hypothesis H6b An organization's collaboration network breadth interacts positively with its prior technological knowledge in terms of its effect on the R&D performance.

4. Methodology

The methodology section comprises a description of the COVID-19 vaccine development case and of the data collection on those organizations active in the COVID-19 R&D in terms of their vaccine candidates, scientific publications, and patents.

4.1. Case description

The pharmaceutical industry is well-suited to study organizational knowledge-related differences, with the coronavirus outbreak specifically offering an opportunity to analyze resource utilization under urgency. The first vaccine candidates that the EU and USA authorized, demonstrated the involved organizations' strong abilities to respond quickly to urgent innovation needs, while other R&D projects failed to do so. Generally, the pharmaceutical industry's R&D processes are time- and cost-intensive and have a high failure rate (Danzon et al., 2005). The trade group Pharmaceutical Research and Manufacturers of America estimates that one treatments' development takes 10 to 15 years, with the final costs averaging of USD 2.6 billion (DiMasi et al., 2016). The development of a new vaccine to combat the global health threat of COVID-19 was expected to take a minimum of 12 to 18 months (Billington et al., 2020). Consequently, drug R&D processes had to be accelerated to react to the pandemic. The conventional new drug development process from discovery to approval and its eventual market launch, is comprised of firmly designated stages (see Supporting Information S1), which increase the costs and time required to develop a new drug (Buonansegna et al., 2014). During the basic research stage, between 5,000 and 10,000 compounds are tested, with approximately 250 entering the preclinical testing, and only between one to five candidates eventually proceeding to human clinical trials (Khanna et al., 2016). The failure risk decreases from the early-stage to the late-stage R&D, while the costs increase (Banerjee and Siebert, 2017).

4.2. Resource exchanges to combat the COVID-19 pandemic

The COVID-19 pandemic, which affected human health, public life, and the global economy, received global attention. The urgent need for treatments and vaccines to prevent the spread of the coronavirus SARS-CoV-2 led to an R&D race for new drugs. The coronavirus outbreak stimulated organizations to mobilize their resources to allow their R&D activities to progress rapidly in order to cope with the pandemic's challenges. Already shortly after the virus' outbreak, there was a call for open science to allow the rapid disclosure of new research results (Homolak et al., 2020). Owing to the research activities' high impact on the global business and society, data and information had never before been so well-documented and so thoroughly shared. Numerous public and private research organizations, agencies, and firms were engaged in collaboration activities and allowed their capabilities and resources to be directly compared, thereby offering a suitable basis for our data analysis. Four candidate vaccines – Pfizer, Moderna, AstraZeneca, and Johnson & Johnson – received EU-authorization during the pandemic's first 18 months (Milken Institute, 2022). We have observed parallels in the collaboration networks (Table 1 and Supporting Information S2).

Organizations played individual roles in the value co-creation process (Figure 1) of each of the projects and exchanged resources to gain a competitive advantage. Universities and other research institutes were mainly involved in the basic science or in the applied research and aimed at a full comprehension of the virus and potential treatments. For the for-profit organizations, the innovation's commercial exploitation was crucial. They therefore participated in the manufacturing and upscaling. External service providers supported the collaboration by specialized individual tasks, such as data management. Highly specialized biotech companies were often engaged in the development, which bigger industrial players supported. Finally, society played a role in the vaccine development, mainly via their various governments. Governmental bodies supported R&D through their research funding programs and decreased the regulatory barriers in order to accelerate the programs' processes, for example, during the vaccine authorization. The USA government, for instance, invested USD 337 million in mRNA research and development during the pre-pandemic period, which had an immediate impact on the most important inventions related to the mRNA COVID-19 vaccines (Lalani et al., 2023). During the pandemic, the US government invested around USD 2.37 billion in mRNA COVID-19 vaccine research and development, including ca. USD 2.26 billion spent on clinical trials (Lalani et al., 2023). Some companies also received substantial governmental financial support. According to the study by Lalani et al. (2023), Moderna obtained USD 10.8 billion, but 81% of this grant was spent on supplying the vaccine. Similarly, the Pfizer and BioNTech alliance received USD 20.4 billion, which was also spent on supplying the vaccine (Lalani et al., 2023). Consequently, public funding contributed greatly to the COVID-19 vaccine's rapid development.

4.3. Dataset and sources

We identified and analyzed organizations reporting activity regarding the COVID-19 vaccine development within the first 18 months after the initial outbreak (until June 2021) in order to take into account those actors involved rapidly in the vaccine R&D against SARS-CoV-2's (Mullard, 2020). Our sources included different databases and organizations' websites, media press releases, and annual reports. We obtained scientific publication data from the Clarivate Web of Science Platform (WoS). Furthermore, we retrieved patent data from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT).

We derived a list of 386 active organizations from the 'COVID-19 Tracker' database that the Milken Institute (2022) offered, recording 265 active R&D vaccine projects. Various organizations were listed as the developers of most of the projects. Duplicates, spelling differences, and miscellaneous cases were manually removed from the list of organizations and sub-departments within an organization were clustered (e.g., the 'Vaccine & Immunotherapy Center at MGH' was assigned to the higher order entity, which in this case, was the 'Massachusetts General Hospital'). We did not assign university hospitals to the affiliated university, because they follow different institutional logics.

We created a dataset of all the publications and patent applications, including the bibliographic meta data from the identified 386 organizations. Additionally, to measure all prior knowledge, we identified all the publications of each organization related to COVID-19 or SARS-CoV-2 by means of a keyword search, which resulted in a total of 863 publications during the period of 2015–2019. We extracted over 95,000 scientific publications from the WoS database on the relevant pathogens, infectious diseases, and vaccines related to novel coronavirus research during the inquiry period for our dataset's 386 organizations. These pathogen and disease-relevant publications constituted the foundation of the organizations' basic research knowledge. Likewise, we collected 4000 patents on similar pathogens, infectious diseases, and vaccines during 2015-2019, which formed the technological basis of the later COVID-19-related R&D. The applied search terms built on the recommendation by Charité Universitätsmedizin Berlin (2021). These search terms are provided in the Supporting Information (S3). We obtained additional data by using publicly available business information from 'Bloomberg' and organizations'

Vaccine candidate's collaborators	Summary
Tozinameran: Pfizer–BioNTech COVID-19 vaccine 11.12.2020 (FDA authorization), 4 collaborators BioNTech (Biotechnology) Pfizer (Pharma firm) Fosun Pharma (Pharma firm) Rentschler Biopharma (Service provider)	The " <i>Pfizer vaccine</i> " (Tozinameran) was the first COVID-19 vaccine to receive EU Emergency Use Authorization in December 2020 and full Food and Drug Administration approval for people aged 16 and older in August 2021. Early development partners were the German, highly specialized, medium-sized biotechnology company BioNTech, a pioneer in mRNA treatments, and the diversified US pharma giant Pfizer, which was specifically concerned with clinical trials, logistics, manufacturing and, providing additional fund- ing. Later partners, like Rentschler Biopharma, which improved the substance purification or Fosun Pharma, which provided access to the Chinese market, sup- ported the manufacturing process
Elasomeran: moderna COVID-19 vaccine 18.12.2020 (FDA authorization), 10 collaborators Moderna (Biotechnology) National Institute of Allergy and Infectious Diseases (NIAID) (National body) Biomedical Advanced Research and Development Authority (BARDA) (National body) Medidata (Service provider) BIOQUAL (Biotechnology) Lonza (Biotechnology) Catalent, Rovi, Baxter BioPharma Solutions, Sanofi (Pharma firms)	For the " <i>Moderna vaccine</i> " (Elasomeran) The Milken Institute's COVID-19 tracker listed ten collabora- tion partners in respect of the " <i>Moderna vaccine</i> " (Elasomeran). This network, led by the US mRNA treatment expert company ModeRNA, had a strong national concentration during the development phase. Governmental R&D institutions, such as the National Institute of Allergy, the Infectious Diseases, and the Biomedical Advanced Research and Development Authority, supported ModeRNA. Additional network partners contributed services, like software solutions, during Mediadata's clinical trials and BIOQUAL's in vivo testing. International biotech and pharma com- panies, like the US Catalent, French Sanofi, Spanish Rovi, and the Swiss Lonza, supported the manufactur- ing process
Oxford–AstraZeneca COVID-19 vaccine 30.12.2020 (UK authorization), 14 collaborators University of Oxford (Research Institution) AstraZeneca (Pharma firm) Advent Srl, IQVIA, Pall Life Sciences (Service providers) Vaccines Manufacturing and Innovation Centre (Research institution) Serum Institute, India (Biotechnology) Vaccitech (Biotechnology) Oxford Biomedica, Cobra Biologics, HalixBV, Catalent, CSL, Merck KGaA (Pharma firms)	A European dominated team of 14 collaborators co- developed the " <i>Oxford-AstraZeneca vaccine</i> ." The team had already involved actors, such as a medium- scale production facility, during the vaccine's early development, and the IQVIA-ranking among the lead- ing healthcare data science companies, to accelerate its clinical trials. The manufacturing sites were spread around the globe
Janssen COVID-19 vaccine 27.02.2021 (UK authorization), 8 collaborators Janssen Pharmaceutical Companies (Pharma firm) Beth Israel Deaconess Medical Center (Research hospital) Emergent BioSolutions (Biotechnology) Biological E (Biotechnology) Grand River Aseptic Manufacturing (GRAM), Catalent, Sanofi, Merck (Pharma firms)	The "Johnson & Johnson vaccine" was the fourth candidate to which that the European Medicines Agency granted a conditional marketing authorization in March 2021. In addition to additional funders and later manufactures, the Johnson & Johnson subsidiary, Janssen Pharmaceuticals, and the Beth Israel Deaconess Medical Center (BIDMC), a Harvard Medical School teaching hospital, drove the vaccine's development. The collaboration partners built the vaccine's development on previous vaccine research aimed at combatting other pathogens, such as HIV and Zika. The final vaccine was based on the same technology used to make the recent Johnson & Johnson Ebola vaccine (Chatterjee, 2021)

Table 1. Successfully authorized COVID-19 vaccine candidates

websites or annual reports. In the absence of data from the previously mentioned sources, we undertook a web-search of publicly available websites and platforms, such as LinkedIn, to supplement missing information. Our research framework is displayed in Figure 2.

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Figure 1. Institutions and their roles in the vaccine development process.





4.4. Operationalization

Scientific knowledge and collaboration activity are found in academic journals and scientific publications and present an organization's R&D activity (Fabrizio, 2009; Della Malva et al., 2015). Various studies have used publications as a proxy for R&D activity and performance (Rafols et al., 2014; Hagel et al., 2017; Yegros-Yegros et al., 2020). Technological

knowledge and collaboration activity are noted in public patent databases. Patents contain information on previous inventions and technologies, but also signal technological perceptiveness. In research, patents are widely utilized indicators to capture an organization's absorptive capacity and innovativeness (Ahuja, 2000; George et al., 2001; Rothaermel and Hess, 2007; Della Malva et al., 2015).

4.5. Dependent variable: R&D performance

We operationalize R&D performance as the stage that an organization's most advanced vaccine candidate experiences. We consider the preclinical stage as the first stage of five (stage 1) which is followed by the clinical trial phases I, II, and III (or stages 2 to 4). Vaccine authorization is the highest possible stage, namely stage 5. Prior literature offered similar ways to measure product innovation performance or R&D performance (Prabhu et al., 2005; Jong and Slavova, 2014; Melnychuk et al., 2021). The authors of these studies measured an organization's innovation and R&D performance by using the number of drug candidates that entered the preclinical or clinical stages for the first time (Jong and Slavova, 2014) or simply the number of drug candidates in the clinical trial phase I (Prabhu et al., 2005; Melnychuk et al., 2021). We therefore identified the most advanced candidate for each organization and measured the R&D performance on a scale ranging from 1 to 5.

4.6. Independent variables: 'prior internal knowledge'

An organization's internal knowledge base comprises scientific knowledge from research publications and technological knowledge from patents. We undertook a keyword search based on recently highlighted potential therapeutic agents against previous coronaviruses and other related infectious diseases (not COVID-19) (Elhusseiny et al., 2020; Pandey et al., 2020) in order to derive an organization's specific knowledge of coronavirus-related infectious diseases.

We measured an organization's *scientific knowl-edge* by the number of publications related to coronavirus infections in the five years prior to the coronavirus outbreak (2015–2019). Likewise, we measured an organization's *technological knowl-edge* by the number of patent applications related to infectious diseases in the five years prior to the coronavirus outbreak (2015–2019). Thereby, we identified an organization's prior internal knowledge as

represented by the patents focusing on either the prior coronavirus's specific experience, or on their experience with infectious diseases and pathogens, or on their vaccine development experience.

4.7. Independent variables: 'prior external knowledge'

Prior external knowledge resulted from prior collaboration partners' knowledge spill-over to the focal organization. In line with the previously introduced scientific and technological knowledge, we included two dummy explanatory variables: *prior scientific collaborations*, which depend on research experience with at least one COVID-19 project collaboration partner in a joint WoS publications, and *prior technological collaboration*, which refers to technology application experience with at least one joint registered patent application prior to the coronavirus outbreak (before 2020).

4.8. Independent variable: 'collaboration network breadth'

In respect of the collaboration network breadth, we identified the spectrum of different organizations within the collaboration projects as the number of different institution types involved in the network. We identified the different institution types in our qualitative analysis of the four authorized vaccines, namely research institutions, biotech and big pharma companies, service providers, hospitals, and governmental bodies. As suggested by Laursen and Salter (2006), we measured the collaboration network breadth as the focal organization's number of diverse institution types of collaboration partners. This is an ordinally scaled measure ranging from zero, meaning no collaboration partners, to 4, implying collaboration with four institutionally different partners. By collecting and analyzing data on the project level of organizations involved in COVID-19 vaccine development projects, we aggregated each organization's number of institution types.

4.9. Control variables

The *organization size* might influence the R&D performance, since larger organizations are more likely to own more resources and assets than smaller ones, and their R&D performances are therefore likely to differ (Leiponen and Helfat, 2010). The *organization size* is defined as the total number of employees (Deeds et al., 2000; Fabrizio, 2009). We derived categories of organizations with <200, <500,

<5,000, and more than 5,000 employees, and a category with an unknown number of employees (others). The higher the number of allocated resources and the higher the potential number of vaccine candidates, the higher the likelihood that one of them will succeed. Organizations with knowledge of and expertise in different types of vaccines' development could respond more rapidly to an urgent crisis, since they could build on their experience with different vaccine types. As such, we controlled for vaccine types competence as the number of different COVID-19 vaccine types in the organization's portfolio (i.e., DNA or RNA-based vaccine, inactivated virus, protein subunit, replicating viral vector, etc.). We included the dummy variable profit orientation: for-profit and non-profit organizations differ in their individual motivations and goals; further their allocation of financial aid differs substantially (Reeves and Ford, 2004). The variable institution type controls for institutional differences, especially for the motivators and innovation drivers (Rothaermel and Hess, 2007). Therefore, all organizations were classified as either a biotech company, pharma company, research institute, hospital, service provider, or a governmental institution (Lee et al., 2018). To account for the current network collaboration research activities, we measured research collaboration as the average number of collaborators per organization in the coronavirus-related WoS publications in 2020 and 2021.

4.10. Estimation method

An ordinal logistic regression (OLR) and a proportional odds model were applied to identify the crucial factors increasing the probability of the organizations' R&D project being shifted to the next product development stage, such as the 'authorization.' OLR is generally used when there is a categorical outcome variable with more than two levels in a natural order. Compared to other regression models for multiclass data, OLR has fewer parameters that need to be estimated. We performed the Brant test to ensure that the proportional odds assumption is not violated (Brant, 1990). Since the data of all of the variables, with the exception of prior scientific collaboration, satisfies the proportional odds assumption, we applied a proportional odds model (Ananth and Kleinbaum, 1997) to test all the hypotheses except H3. The Brant test indicated that the prior scientific collaboration's influence was not proportional across each category of the prior scientific collaboration; consequently, we estimated a multinomial logistic regression model with which to test H3. We defined the 'preclinical

stage' as a reference category in the multinomial logistic regression model.

The high variety of organizations in our sample led to some variables having outlier values, which could result in an estimation bias. We therefore excluded observations with extreme values under the 1% percentile and above the 99% percentile in respect of the explanatory variables prior internal scientific and technological knowledge. When we excluded the outliers, the dataset contained 386 observations.

5. Empirical results

The correlation matrix and the variables' descriptive statistics are displayed in Tables 2 and 3. The pairwise correlations between the explanatory variables are low or moderate. We calculated the variance inflation factors (VIFs), finding that multicollinearity is not present in our data, since the mean VIF value is 1.4, which does not indicate a multicollinearity issue (Bühner and Ziegler, 2012; Cohen et al., 2015). The nine proportional odds models' results of the R&D performance factors are presented in Table 4. We summarize the robustness checks presented in the Supporting Information (S4).

Model 1 is a baseline model only comprising control variables. In respect of the control variables, we observe significant differences in the R&D performance, depending on the organization size, the number of vaccine candidates, and certain institution types. The larger the organization, the greater the chances of reaching the next development stage in the R&D performance process (p < 0.001 in all groups, except in 'others'). In respect of the largest organization group of more than 5000 employees, the probability of transiting a vaccine candidate is specifically 6.3 times higher ($\beta = 1.99, p < 0.001$) than in the smaller organizations of up to 200 employees (the reference category). Compared to the biotech companies, research organizations and hospitals have odds that are 83% and 81% less than those of biotech companies ($\beta = -1.78$ and $\beta = -1.68$ at p < 0.05) of having their candidate vaccine reaching the next stage. No differences were observed in respect of the variables 'vaccine types competence,' 'for-profit orientation,' and 'research collaboration.'

Models 2 to 5 each included all the effects in respect of the four independent variables' R&D performance. Model 2 showed that the variable 'prior scientific knowledge' had no significant effect; H1 was therefore rejected. Model 3 showed that the variable 'prior technological knowledge' had a significant positive association (β =1.18, p<0.01), which supported H2. This implied that a

1able 4	. Correlation matrix										
	Variable	1	2	3	4	5	9	7	8	9	10
-	R&D performance	1									
7	Prior scientific knowledge	-0.063	1								
Э	Prior technological knowledge	0.222^{***}	0.105*	1							
4	Prior scientific collaboration	0.162^{**}	0.221 * * *	0.232***	1						
5	Prior technological collaboration	0.113*	0.075	0.373 * * *	0.228***	1					
9	Collaboration network breadth	0.400^{***}	0.005	0.123*	0.402***	0.086	1				
L	Number of vaccine R&D projects	0.213^{***}	0.003	0.177 * * *	0.289***	0.046	0.340***	1			
8	Vaccine types competence	0.097	0.023	0.075	0.207***	-0.012	0.145**	0.584***	1		
6	Organization size	0.082	0.230***	0.160^{**}	0.213^{***}	0.095	0.097	0.062	0.151^{**}	1	
10	Research collaboration	-0.057	0.122*	0.042	0.104*	0.047	0.011	0.044	-0.019	0.215***	1
n = 386.	001;										
b < 0.1	11;										

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one-unit increase in prior technological knowledge (100 patent applications) raised the odds by 2.3 of the vaccine candidate transitioning to the next stage. The likelihood ratio test (LRT) indicated that the model fit (LRT=9.75, p < 0.01) had improved. The predictor's integration is therefore supported. H4 cannot be rejected as a significant association was observed in respect of prior technological collaborations (Model 4, $\beta = 0.68$, p < 0.1), even though the effect was only significant at the p < 0.1level. Consequently, the chances of the vaccine candidate of organizations with prior technological collaboration experience reaching the next stage, are 97% higher compared to organizations with no such previous experience. In Model 5, we find support for H5, namely that the collaboration network breadth also facilitates the R&D performance. Compared to organizations with no collaboration partners in COVID-19 projects, the odds of organizations collaborating with two partners from other institution types reaching the next innovation stage increased by 1.6 times ($\beta = 0.94$, p < 0.001), while the chances of organizations collaborating with three different types of partners grew by 8.9 times ($\beta = 2.30$, p < 0.001), and the odds of the vaccine candidate of organizations collaborating with four different institutional partners transitioning to the next development stage were elevated by 37.9 times (β =3.66, p<0.01). The LRT also confirmed the predictor's inclusion (LRT=43.53, p < 0.001). Models 6 and 7 integrated the collaboration network breadth's interaction effects and those of, respectively, prior scientific knowledge and prior technological knowledge. In both models, the collaboration network breadth's interaction effect regarding four different institutional partners was significantly positive in terms of prior scientific knowledge (β =79.81, p<0.001) and prior technological knowledge ($\beta = 501.40, p < 0.001$); consequently, H6a and H6b cannot be rejected. The fit of the two models also improved (Model 6: LRT = 57.14, p < 0.001; Model 7: LRT = 60.58, p < 0.001). The full Model 8 integrated all the direct and interaction effects. This model's likelihood ratio test indicated the model's improved fit (LRT=61.85, p < 0.001) compared to the base model (Model 1), which supported the independent and interaction variables' integration into the full model.

Turning to the prior scientific knowledge collaboration hypothesis, we find support for H3 in the multinomial logistic regression model (Table 5), since the prior scientific collaboration's coefficients in the clinical trials' phase 1 and in the authorization stage are positive and significant (clinical trials

p < 0.05

	Variable	Mean	SD	Min.	Max.
1	R&D performance	2.20	1.39	1	5
2	Prior scientific knowledge	0.02	0.08	0	0.7
3	Prior technological knowledge	0.10	0.27	0	2.12
4	Prior scientific collaboration	0.26	0.44	0	1
5	Prior technological collaboration	0.06	0.24	0	1
5	Collaboration network breadth	1.17	1.04	0	4
7	Number of vaccine R&D projects	1.18	0.69	1	9
3	Vaccine types competence	1.15	0.48	1	4
)	Organization size	2.49	1.35	1	5
10	Research collaboration	4.80	9.38	0	146.83

 Table 3. Descriptive statistics

Notes: n=386; prior scientific knowledge and prior technological knowledge were divided by 100.

phase 1: $\beta = 0.88$, p < 0.05; authorization: $\beta = 2.63$, p < 0.001) compared to the 'preclinical stage' reference category. Compared to the organizations in the preclinical stage that have never undertaken any research collaboration with one another on the coronavirus, or on related diseases before, organizations with such prior scientific collaboration experience will have a 1.4 times higher chance of the vaccine candidate transitioning in the clinical trials' phase 1. Similarly, organizations with prior scientific collaboration experience will have a 12.9 times higher chance of the candidate vaccine transitioning in the authorization stage. Furthermore, the Akaike information criterion (AIC) confirms the prior scientific collaboration's inclusion into the model, since its value in the model with only control variables only (AIC = 1,015.65) is higher than its value in the model with prior scientific collaboration as the explanatory variable (AIC=990.63) (Cavanaugh and Neath, 2019).

To visualize the estimated interaction effects, we plotted the predicted probabilities of reaching the R&D performance stages (as separate stages) as a function of the prior scientific knowledge and the prior technological knowledge at different levels of the collaboration network breadth (no partner, 1, 2, 3, and 4 partners) in Figures 3 and 4.

Figure 3 indicates that, in the preclinical vaccine development stage, organizations with a high level of prior scientific knowledge benefit the most from collaborations with one or two partners from different institution types, since such organizations have the greatest chance of reaching and completing this vaccine development stage. Figure 3 shows that an organization's probability of reaching and completing the clinical trials' phases 1 and 2 does not necessarily depend on the number of collaborating partners from different institution types. In the clinical trials' phase 3, organizations profited more from collaborating with three or more different partners. In the authorization stage, organizations with a high level of prior scientific knowledge, profit to the highest degree if they collaborate with partners from four different institution types. As such, there are large differences in the probabilities of reaching and completing different development stages. In the first stage (preclinical stage), a high level of scientific knowledge helps organizations reach and complete this stage, especially if they work alone, or with one or two different institutional partners. In this stage, organizations' prior basic research results and accumulated knowledge could lead to rapid research results, such as those concerning the coronavirus. In the other R&D stages, basic research knowledge plays a less important role in potential product development.

Figure 4 shows that, in the preclinical stage, organizations with low levels of prior technological knowledge have the best chances of reaching and completing this vaccine development stage if they either do not collaborate, or collaborate with fewer partners from different institution types. In this phase, basic research knowledge might be highly important, whereas applied product knowledge embedded in patent applications is less relevant for preclinical research. Conversely, in the authorization stage, applied technological knowledge is highly relevant. In this stage, organizations with a high level of prior technological knowledge profit most from it if they collaborate with three or four partners from different institution types.

In addition, we performed several analyses to check our results' robustness (see Supporting Information S4 for details). We ran an analysis on the entire dataset. The results remained similar to those in Table 4. Similar to H3's test, we conducted multinomial logistic regressions in respect of prior scientific knowledge, prior technological

Table 4. Effects on R&D performance								
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Number of vaccine R&D projects	0.36 (0.18)*	0.36 (0.18)*	0.29 (0.18)	0.35 (0.18)#	0.01 (0.19)	-0.09 (0.19)	-0.29 (0.22)	-0.29 (0.22)
Vaccine types competence	0.00 (0.25)	0.00 (0.25)	0.03 (0.25)	0.03 (0.25)	0.05 (0.27)	0.10 (0.27)	0.10 (0.28)	0.11 (0.29)
Organization size (under 500)	$1.42 (0.40)^{***}$	$1.43 (0.40)^{***}$	$1.41 (0.40)^{***}$	$1.44(0.40)^{***}$	$1.64 (0.40)^{***}$	$1.64 (0.41)^{***}$	$1.60(0.41)^{***}$	$1.59 (0.41)^{***}$
Organization size (under 5000)	$1.72 (0.30)^{***}$	$1.72(0.30)^{***}$	$1.62(0.30)^{***}$	$1.66(0.31)^{***}$	$1.55(0.31)^{***}$	$1.43 (0.31)^{***}$	$1.39(0.31)^{***}$	$1.38(0.31)^{***}$
Organization size (over 5000)	2.04 (0.37)***	2.03 (0.37)***	$1.80(0.38)^{***}$	1.98 (0.37)***	1.82 (0.37)***	1.52 (0.39)***	1.44 (0.39)***	$1.42(0.39)^{***}$
Organization size (others)	-0.46 (0.71)	-0.46 (0.71)	-0.58 (0.71)	-0.49 (0.71)	-0.42 (0.73)	-0.58 (0.73)	-0.59 (0.72)	-0.63 (0.72)
Organization profit type (non-profit)	-0.50 (0.71)	-0.51 (0.72)	-0.39 (0.70)	-0.52 (0.71)	-0.19 (0.78)	-0.02 (0.77)	0.02 (0.78)	0.04 (0.77)
Institution type: Pharma	0.10(0.33)	0.10(0.33)	0.14(0.33)	0.09 (0.33)	0.04 (0.33)	0.09 (0.34)	0.14(0.34)	0.14 (0.34)
Institution type: Research	-1.75 (0.77)*	-1.78 (0.77)*	-1.79(0.76)*	-1.73 (0.77)*	-1.99 (0.83)*	-2.07 (0.82)*	-2.05 (0.84)*	-2.05 (0.83)*
Institution type: Hospital	-1.69 (0.83)*	-1.67 (0.83)*	-1.59(0.82) [#]	$-1.59(0.83)^{\#}$	-1.85 (0.89)*	-1.77 (0.89)*	$-1.74(0.89)^{\#}$	-1.75 (0.89)*
Institution type: Governmental institution	0.99 (0.93)	0.99(0.93)	1.04 (0.92)	1.05(0.93)	0.63(0.99)	0.65 (0.97)	0.67 (0.98)	0.67 (0.98)
Institution type: Services	0.26 (0.56)	0.27 (0.56)	0.41 (0.56)	0.32 (0.56)	-0.23 (0.57)	-0.05 (0.57)	0.09(0.58)	0.10(0.58)
Research collaboration	-0.00 (0.01)	-0.00(0.01)	-0.00(0.01)	-0.00(0.01)	-0.00(0.01)	-0.00 (0.01)	-0.00(0.01)	-0.00(0.01)
Intercept preclinicallClin. trials phase 1	0.61 (0.29)*	0.61 (0.29)*	0.64 (0.29)*	0.64 (0.29)*	0.69 (0.34)*	0.75 (0.34)*	0.56 (0.37)	0.60(0.38)
Intercept clin. trials phase 1lClin. trials phase 2	1.11 (0.29)***	1.11 (0.29)***	$1.15(0.29)^{***}$	$1.14(0.29)^{***}$	$1.22(0.34)^{***}$	1.28 (0.35)***	$1.10(0.38)^{**}$	$1.13(0.39)^{**}$
Intercept clin. trials phase 2lClin. trials phase 3	2.14 (0.31)***	$2.14(0.31)^{***}$	2.19 (0.31)***	2.17 (0.31)***	2.32 (0.36)***	2.41 (0.37)***	2.21 (0.40)***	2.25 (0.40)***
Intercept clin. trials phase 3lAuthorization	3.71 (0.37)***	3.71 (0.37)***	3.82 (0.37)***	3.76 (0.37)***	4.11 (0.42)***	4.28 (0.44)***	4.13 (0.45)***	$4.17 (0.46)^{***}$
Direct effects								
Prior scientific knowledge (PSK)		0.64(1.48)				1.56 (2.38)	0.01 (1.58)	1.52 (2.39)
Prior technological knowledge (PTK)			$1.18(0.38)^{**}$			1.34 (0.44)**	1.95 (1.27)	1.88 (1.27)
Prior technological collaboration				$0.68(0.41)^{\#}$		0.35(0.46)	0.34 (0.47)	0.39(0.47)
Collaboration network breadth: 1 partner (CNB 1P)					0.25 (0.26)	0.24 (0.27)	0.26(0.28)	0.31 (0.29)
Collaboration network breadth: 2 partner (CNB 2P)					0.94 (0.28)***	0.93 (0.30)**	$0.98(0.31)^{**}$	$1.03(0.32)^{**}$
Collaboration network breadth: 3 partner (CNB 3P)					2.30 (0.39)***	2.41 (0.42)***	2.20 (0.43)***	2.19 (0.45)***
Collaboration network breadth: 4 partner (CNB 4P)					$3.66(1.40)^{**}$	3.75 (1.48)*	3.22 (1.77)#	3.25 (1.77)#
Interaction effects								
PSK×CNB 1P						-4.17 (3.75)		-3.84 (3.84)
PSK×CNB 2P						-2.88 (4.46)		-2.93 (4.46)
PSK×CNB 3P						-1.41 (3.71)		-0.67 (3.61)
PSK×CNB 4P						79.81 (0.00)***		1254.28 (0.00)***
PTK × CNB 1P							-0.96(1.41)	-0.74 (1.42)
PTK × CNB 2P							-0.67 (1.43)	-0.60 (1.43)
PTK×CNB 3P							5.53 (4.18)	5.76 (4.20)

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Table 4. (Continued)								
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
PTK ×CNB 4P							501.40 (0.00)***	369.58 (0.00)***
AIC	987.37	989.19	979.63	986.69	951.85	952.23	948.79	955.53
Log likelihood	-476.69	-476.59	-471.81	-475.35	-454.92	-448.12	-446.40	-445.76
LRT	Base	0.18	9.75**	2.68	43.53***	57.14***	60.58***	61.85***
Note: $n = 386$; proportional odds logistic regular AIC, Akaike information criterion; CNB, co *** $p < 0.001$; ** $p < 0.01$; ** $p < 0.01$; * $p < 0.01$; * $p < 0.01$; * $p < 0.05$; * $p < 0.$	ression; unstandardized c llaboration network brea	oefficients; standau dth; LRT, likelihoo	rd errors in parentl d-ratio test; PSK,	heses; prior scient prior scientific kn	ific knowledge and owledge; PTK, priv	l prior technological kn or technological kn	il knowledge were o Iowledge.	livided by 100.

knowledge, prior technological collaboration, and the collaboration network breadth. The preclinical stage was a reference category. The results showed some differences between the preclinical stage and the other R&D performance stages. In addition, we included R&D expenditures to control for the absorptive capacity. Owing to the available R&D expenditure data's scarcity, the dataset contained only 83 observations. Furthermore, due to the drastically reduced dataset, only the collaboration network breadth's effects were significant. We moreover ran an additional analysis to control for COVID-19 projects' received funding. The results remained similar to the main results. We furthermore tested the possible interaction effects of the collaboration network breadth and the prior scientific/technological collaboration on R&D performance.

6. Discussion

By supporting all the hypotheses, except H1, the study revealed the relevant organizations' knowledge-related capabilities in respect of rapid R&D performance in the pharmaceutical industry under urgency. The prior knowledge base is partially decisive for utilizing knowledge under urgency. We did not find any evidence that prior scientific knowledge has a positive effect on R&D performance. This contradicts earlier pharmaceutical industry studies under normal conditions (Fabrizio, 2009; Kuo et al., 2019). Xu et al. (2013) found an inverted U-shaped relationship between internal prior knowledge and innovative performance in a pharmaceutical firm setting. In line with March (1991), their findings indicated that, specifically, in-depth prior knowledge hinders firms from generating new knowledge through high-risk experimentation and exploration. Firms with in-depth knowledge, enhance existing technologies rather than neglecting mechanisms used to integrate novel methods. Furthermore, prior scientific knowledge could be more beneficial during the earliest R&D stage (compare Figure 3), thereby reflecting its function of enhancing organizations' absorptive capacity to foster applied knowledge's assimilation and exploitation in the later development stages.

Prior technological knowledge's positive effect supports the finding that retained knowledge from prior R&D experiences is an important internal resource of knowledge creation and recombination, and is also transferred to related future R&D projects (Marsh and Stock, 2006; Kuo et al., 2019). A

	Clinica phase 1	ıl trials I	Clinica phase 2	ll trials 2	Clinica phase 3	l trials 3	Authorizat	tion
	β	SE	β	SE	β	SE	β	SE
(Intercept)	-2.70	0.62***	-1.50	0.50**	-2.45	0.59***	-3.91	0.74***
Number of vaccine R&D projects	0.70	0.51	0.51	0.45	1.20	0.46**	0.57	0.51
Vaccine types competence	-0.23	0.48	-0.07	0.43	-0.57	0.51	-0.05	0.59
Organization size (under 500)	0.35	0.88	0.49	0.67	2.69	0.61***	0.64	1.34
Organization size (under 5000)	0.72	0.58	0.80	0.45 [#]	2.31	0.49***	1.89	0.66**
Organization size (over 5000)	-0.14	0.75	0.89	0.55	2.57	0.63***	2.91	0.81***
Organization size (others)	-1.31	1.32	-1.64	1.56	-1.54	1.38	-13.80	0.00***
Organization profit type (non-profit)	0.98	1.34	0.83	1.21	-0.49	1.38	-1.15	1.47
Institution type: Pharma	0.76	0.64	-0.10	0.51	-0.04	0.52	0.61	0.70
Institution type: Research	-1.45	1.44	-2.21	1.28 [#]	-2.10	1.47	-3.72	1.85*
Institution type: Hospital	0.24	1.45	-2.88	1.59 [#]	-2.17	1.53	-1.87	1.74
Institution type: Governmental institution	1.73	1.83	0.02	1.84	2.79	1.85	2.67	2.22
Institution type: Services	-0.42	1.33	-0.38	0.89	-0.83	0.98	1.22	1.01
Research collaboration	0.01	0.01	0.00	0.02	-0.04	0.04	-0.04	0.06
Direct effects								
Prior scientific collaboration	0.88	0.43*	0.53	0.37	-0.49	0.54	2.63	0.56***

Table 5. Effects of prior scientific collaboration on R&D performance (different stages of R&D performance)

The multinomial logistic regression's reference category is "preclinical stage"; unstandardized coefficients; standard errors; n=393. A model with control variables only has an Akaike information criterion (AIC) of 1,015.65; a model with prior scientific collaboration as an independent variable has an AIC of 990.63.

****p*<0.001; ***p*<0.01;

 $p^* < 0.05;$ $p^* < 0.1.$



Figure 3. Interaction effects of the collaboration network breadth and organizations' prior scientific knowledge on R&D performance.

broad technological knowledge base enhances the innovative performance and offers more opportunities for internal knowledge recombination (Leiponen and Helfat, 2010). Organizations benefit from leveraging their internal knowledge and, therefore, need to relate to knowledge of previous drug candidates,



Figure 4. Interaction effects of the collaboration network breadth and organizations' prior technological knowledge on R&D performance.

or of other infectious diseases' existing patents (Harrison, 2016). Organizations with experience of other, newly emerged diseases might have developed valuable knowledge that might have increased their ability to respond rapidly to the current pandemic and to develop potential drug candidates. The more knowledge an organization has of concrete drug development in related diseases, the higher its chances of reaching and completing a development stage, including the authorization stage (Cockburn and Henderson, 2001).

The need to develop COVID-19 vaccine candidates rapidly meant that the lacking competencies could not only be developed internally, but also needed to be accessed externally. During urgency, the prior collaboration network was critical, since new formal and informal ties could not be developed promptly. Both their prior scientific and technological collaboration increased the organizations' R&D performance. This observation strengthens the relevance of proper embeddedness in an existing network, and supports the discussion on R&D activities' long-term effect. The formation of networks is a long-term investment, while the capability to form networks and alliances efficiently is based on experience (Kirchhoff et al., 2020). Owing to the urgent need for an efficient response, organizations should rather collaborate with partners they know and trust (Gilsing et al., 2008; Fry et al., 2020). A larger network offers access to more resources, while previous collaborations ensure that new R&D projects will connect quickly. Scientific collaboration's positive role is in line with the observation that pharmaceutical firms, which failed to develop internal resources, could profit from alliances within the pharmaceutical industry (Fernald et al., 2017). Together with the finding that internal scientific knowledge does not necessarily promote R&D performance, prior collaboration is highly valuable for firms endeavoring to access collaboration partners' deep knowledge.

The findings reveal that a collaboration network breadth has a positive effect on R&D performance. Research-oriented organizations explore new approaches, techniques, and methods, but rely on external support to test and verify their usability. Incumbent firms specifically have large product portfolios and strong down-stream resources for clinical testing, production, and sales. In collaboration projects, incumbents and biotechnological start-ups, for instance, recombine unlinked knowledge and resources effectively. This need for diverse networks also includes collaborations with universities (Dong and McCarthy, 2019). Public research institutions mostly conduct fundamental research, such as chemical structure identification, transmission, and replication mechanisms. In the pharmaceutical industry, public research institutions and hospitals deliver scientific knowledge (Cassiman et al., 2008; Fabrizio, 2009) and focus on the early development phases (de Vrueh and Crommelin, 2017). Conversely, pharmaceutical firms take on coordination and management functions in respect of early development (Kaitin, 2010; Rafols et al., 2014), only becoming active in respect of late-stage development, manufacturing, distribution, and marketing (Hoang and Rothaermel, 2010).

Collaborations with partners from different institution types are particularly important if

organizations have sufficient prior scientific and technological knowledge. Our results show that, in the early development stage, organizations with a high level of prior basic scientific knowledge could leverage this if they were to focus on collaboration with one or two institutionally different partners. In general, in the early development stage (e.g., a drug and vaccine discovery stage), basic research knowledge is of greater significance than applied knowledge embedded in patents (Stevens et al., 2011). In this early stage, organizations with a low level of prior technological knowledge benefit more if they collaborate with fewer partners from different institution types. In an early R&D stage, collaborations with a few, institutionally different, partners allow organizations to acquire complementary external knowledge more efficiently, since the transaction costs of institutionally similar partners are low (Bruneel et al., 2010). Our findings also reveal that, in the late development stages, it is crucial to collaborate with more partners from different institution types, since each of them contributes their own, specific scientific knowledge, product development knowledge, and experience (Schuhmacher et al., 2016), thereby fostering the successful completion of the late development stage.

The research setting, data measurement, and interpretation of the study have limitations. In terms of the COVID-19 pandemic's research setting, the rather precompetitive R&D, first, limits the research findings' transferability and generalizability. Second, research projects in explorative development of new treatments and vaccines have not been differentiated from rather exploitative drug repositioning projects, which are expected to proceed faster to their late-stage clinical trials, because they already have a proven and sufficient safety profile. Finally, various organizations do not seem to be connected to the network; however, this seems to be due to the research setting, because the network only displays the connections between organizations with vaccine candidates in pre-clinical or clinical development. Unconnected organizations could still acquire the relevant external knowledge from their partners who do not participate actively in COVID-19 R&D, and are therefore not represented in the network. Regarding the measurement, we highlighted public institutions and small firms' integration, but incentives to publish research results vary between organizations (Rafols et al., 2014). Public research institutions focus on fundamental knowledge and have a broader research interest scope (Cassiman et al., 2008), resulting in more publications compared to pharmaceutical firms. In addition, publication quality was not considered in this study, although high-quality publications indicate the generation of more relevant new knowledge than multiple low-quality publications. Despite the common use of patents as a proxy for prior technological knowledge, not all R&D outcomes are patentable or they are exploited in other ways. The collaboration network breadth measurement focusses on the direct ties between organizations only, while indirect ties also offer opportunities to transfer knowledge (Belderbos et al., 2016). Large pharmaceutical firms might specifically choose to access scientific knowledge from universities, through their connections with biotechnological firms. We tested our dataset under the proportional odds assumption, which allowed us to apply a proportional odds logistic regression as an empirical model for testing all the hypotheses with the exception of H3. The proportional logistic model's results in respect of the preclinical stage differ entirely from those of the other stages (see the figures of the plotted direct effects of prior technological knowledge, prior technological collaboration, and collaboration network breadth in the Supporting Information S5-S7). The multinomial logistic regression's results indicate that prior scientific collaboration has different effects in the preclinical stage than in clinical trials' phase 1 and in the authorization stage (see the figure of prior scientific collaboration's plotted direct effects in the Supporting Information S8). However, within this study's scope, the preclinical stage only applies in respect of the entire vaccine discovery, research, and development process. Future research should investigate the success factors of the preclinical stage's knowledge-related and collaboration network.

7. Conclusion and contribution

Given the Spanish flu, Ebola, Zika, and the Middle East respiratory syndrome (MERS), SARS-CoV-2 will not have been the last pandemic to threaten society. Increased mobility, urbanization, and climate change could even exacerbate its spread (Bloom et al., 2017). This likelihood highlights the relevance of our study on potentially rapid vaccine development in future. Furthermore, we suggest that the research findings could also be transferred to regular pharmaceutical R&D, because there is a growing need to accelerate R&D productivity.

Our study contributes to the innovation and knowledge management literature in several ways. First, it extends the KBV literature (Grant, 1996b) by suggesting that organizations' prior domainspecific technological knowledge is crucial for organizations' rapid knowledge application in related domains, but at different R&D stages. Our paper contributes to open innovation research (Schuhmacher et al., 2018; Ahn et al., 2019; Patrucco et al., 2022) by highlighting prior linkages' and alliance experiences' importance for rapid knowledge and capabilities exploitation during different R&D stages in domain-specific scientific and technological networks. Furthermore, by providing the empirical evidence that organizations could reach and complete R&D performance stages rapidly if they were to forge alliances with other institutional actors, our research extends prior literature on institutional boundary spanning (Lundberg, 2013) by explicating the contributions that collaborations with institutionally different partners make in the specific biotech and pharmaceutical industry context.

Furthermore, our findings suggest that the urgently built inter-institutional collaborations' success depends on the level of organizations' prior scientific and technological knowledge in specific related domains. Although coordinating collaboration activities and integrating knowledge from different institutional collaboration partners might be challenging (Bruneel et al., 2010; Evans and Austin, 2010), our study provides empirical evidence that organizations with a sufficient knowledge base benefit from collaborating with intuitionally diverse partners in terms of successful product candidate transitions to the next development stage. This complements the literature suggesting that the need for collaboration to accelerate innovation speed in times of crises (Geurts et al., 2022).

Our study provides several evidence-based managerial implications for undertaking R&D in critically urgent scenarios. During times of crises, R&D managers should emphasize the exploitation of previously acquired knowledge-related capabilities. Our results further imply that organizations profit from diverse prior knowledge and alliances in domains related to the current urgent issue's domain. Findings from and experience with previous R&D projects strengthen an organization's ability to undertake future R&D, and allow organizations to respond rapidly and efficiently to urgent R&D issues.

As such, our study suggests that forming strategic alliances in diverse domains enables organizations to use their collaborative linkages effectively in scientific and technological networks for new and urgent R&D projects. These networks could then exploit knowledge rapidly in related domains. Our study therefore indicates that organizations' R&D projects and collaboration activity have a positive, long-term effect on R&D performance. Internal knowledge enables organizations to collaborate successfully, while extending externals' knowledge base could offer the potential to recombine knowledge to produce new innovations (Melnychuk et al., 2021). Managers should also optimize their firm's focus on the internal basic research, which should be based on the firm's capabilities, in order to enhance its capability to leverage public institutions' scientific knowledge efficiently and to bridge organizational and knowledge differences. Furthermore, our study recommends that R&D managers should collaborate with different institutional partners, especially during potential products' late development stages, since different institutional collaborators have diverse complementary resources and capabilities that could be effectively integrated into specific R&D projects. In conclusion, incumbent pharmaceutical firms should connect to startups, such as biotech firms, and involve research institutions in their work in order to speed up their R&D processes effectively and allow them to develop the next radical innovation, like an effective treatment for COVID-19.

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Data availability statement

The data that supports the findings of this study are available in the supplementary material of this article. These data were derived from the following resources available in the public domain: *Web of Science Database* (https://www.webofscience.com). *EPO Patstat Patent Database*, VERSION 2.7.4 (https://data.epo.org/expert-services/index.html). *Milken Inst. COVID-19 Treatment & Vaccine Tracker* (https://covid-19tracker.milkeninstitute.org/). Further data can be provided by the corresponding author upon request.

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