OXFORD ECONOMICS

THE STATE OF SCIENTIFIC RESEARCH PRODUCTIVITY

HOW TO SUSTAIN A CRITICAL ENGINE OF HUMAN PROGRESS

NOVEMBER 2021

Merck KGaA
Darmstadt, Germany

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FOREWORD

This report reviews the current health of global scientific research - a fundamental force that propels humanity forward. Scientific and technological advancements are integral to improving the quality and longevity of human life, as well as the health of our economy, planet, and biosphere. Therefore, a review of scientific research can serve as a barometer to help forecast potential changes in our ability to understand and influence the future.

As a global leader in electronics, healthcare, and the life sciences with a proud history of achievement extending back to 1668, Merck KGaA, Darmstadt, Germany has long been dedicated to advancing human progress with the latest science and technologies.

We felt it was important to direct our curiosity towards the health of scientific research itself. Is the scale and productivity of research declining? If so, how and why? Moreover, what can the scientific community, policymakers, and other stakeholders do to further boost productivity? The answers to such questions are important for Merck KGaA, Darmstadt, Germany as well as our partners, scientific peers, and society overall.

When we commissioned this report in 2020, there was sufficient reason to be concerned. A growing body of evidence in literature pointed to a decline in research productivity across many countries and sectors. This report has highlighted that while some of these concerns are valid, there is no simple answer. Levels of productivity vary based on factors including scientific complexity, the level of pressure to publish, sources of funding, and how parties choose to collaborate or outsource.

Many experts who contributed to this report have suggested ways to further boost research productivity. To review the process of scientific funding itself to see how it can become more efficient and impactful. To make governments

more aware of science and its public value. To prioritise scientific quality over publication timing. To expand the visibility and accessibility of results. To encourage more frequent collaboration between peers. And, to introduce more programs to attract and retain top talent. Many of these suggestions have merit and deserve broader discussion.

At the time of this report's publication, there were many promising signs of a positive overall shift in research momentum. The rapid development of COVID-19 vaccines, therapeutics, and diagnostics alleviated the total potential harm of the pandemic. It showed the world what is possible when science and technology is mobilised to confront a common threat. These efforts contributed to the number of articles published in scientific journals breaking records in 2020, while public awareness in science and scientists reached heights rarely seen for decades.

Scientists, policymakers, and, more broadly, we as a society should strive to ensure that this pandemic serves as an inflection point. We cannot afford to waste this opportunity to provide the scientific community with the support and resources needed to aim even higher. Suppose that we allow the momentum of scientific research to slow. In that case, we might miss pivotal opportunities to address critical issues such as climate change, future pandemics, and the supply of water, food, and scarce resources including energy.

It must be our collective goal to foster an environment that allows curious scientific minds to outperform in an increasingly complex and connected world. Let us together seize this moment to accelerate the scale and speed of scientific research productivity.

Belén Garijo, Chair of the Executive Board and CEO, Merck KGaA, Darmstadt, Germany

Few subjects excite economists as much as productivity: the measure of how much work is required to deliver a given output. Increasing productivity is an essential driver of the economic growth that can help people around the world escape poverty and enjoy a better quality of life. This is especially true in the realm of scientific research, which powers innovation in so many fields that enable humanity to survive and thrive.

Our team at Oxford Economics was delighted at the chance to work with Merck KGaA, Darmstadt, Germany on this ground-breaking program. We had seen reports suggesting that productivity in scientific research has slowed in recent years, and we wrestle frequently with tough questions around related trends in the digital world. Now our economists and editors had an opportunity to collaborate with a world-class partner to explore these issues and their profound implications for our shared future.

Scientific research is far too huge an endeavour to yield a single, simple answer to our core question about productivity rates, much less the factors driving changes in these rates. Science after all is a multifaceted, global enterprise with hotspots of innovation and history-making breakthroughs, along with important ongoing work in far more mature fields of inquiry, all carried out along a continuum from research labs through to product-development organizations.

Tackling a topic this vast and varied required a broad spectrum of research techniques, from econometric analysis and modelling to a global survey and in-depth conversations with experts. This effort involved several different parts of our company around the globe and close collaboration with our partners at Merck KGaA, Darmstadt, Germany.

The top-line finding of our research is that we did not find a generalised slowdown in scientific research productivity, but our work points to particular areas where it appears to be lagging – where getting the same level of output requires more and more resources in terms of time, money, and talent.

Most importantly, the findings indicate a number of ways that organizations can begin to address these shortfalls. Far from a one-size-fits-all solution, we highlight remedies that should be relevant and accessible where needed to companies, universities, and governments involved in this most essential of human activities.

Adrian Cooper, CEO,
Oxford Economics

EXECUTIVE SUMMARY

In this paper we define scientific research productivity as the relationship between research inputs, such as funding levels or number of researchers, and scientific outputs, including academic publications and granted patents.

Scientific research is a critical driver of economic growth and improvements in standards of living. Indeed, the OECD finds that a 1% increase in research and development spending boosts economic productivity by up to 0.4%.[1] Measuring the productivity of this scientific research is therefore an important task. For businesses, it is important to measuring return on investment for shareholders. For publicly-funded institutions, it is important to ensure that taxpayer money is being used effectively.

A growing body of literature points to a decline in the productivity of essential aspects of scientific research. If true, this drop-off should be a pressing concern for policymakers, businesses, and research organisations.

Merck KGaA, Darmstadt, Germany and Oxford Economics have carried out an in-depth study to understand whether the productivity of scientific research is indeed falling and to explore the key drivers of this important engine of progress. To investigate the issue, we interviewed more than thirty researchers around the world, fielded a survey of 3,500 scientists in seven countries, conducted original econometric analysis, and carried out a thorough review of existing literature.

[1] OECD, *R&D and Productivity Growth: Panel Data Analysis of 16 OECD Countries*, 2001. Productivity is measured by multifactor productivity (MFP), which is the residual once the contributions of labour and capital are subtracted from GDP growth.

SCIENTIFIC RESEARCH PRODUCTIVITY IS A COMPLEX ISSUE WITH NO CONCLUSIVE OVERALL TREND

Through this holistic, multi-channel review we find that there is no single conclusive answer to the question of whether scientific research productivity is declining that is consistent across all countries and all fields of research. Rather, we find a complex situation with different conclusions by country, industry and source of information.

We focus specifically on scientific research in this paper, rather than looking at the broader field of business innovation, which can include creating new business models without necessarily involving any scientific research.

Measuring productivity is a non-trivial challenge that, combined with the vastness of the subject, makes sweeping statements about scientific research trends difficult. To further complicate the issue, public data are only widely available for a small number of the metrics used to measure research productivity. We have used these available data sources in our analysis but as we explore in this report, these are not flaw-free measures. Furthermore, many of our survey respondents reported that other metrics, based on internal data, were the most important ways for them to keep track of research productivity, including 65% saying that the number of successful trials or studies per dollar of research budget was the greatest focus for their organisation.

Using publicly available data, we find that productivity in applied research and experimental development (later stages of the research cycle where knowledge is applied to a particular aim) has declined in many countries, when measured as the number of patents granted divided by amount of R&D spending. There is also evidence of a decline in particular industries such as pharmaceuticals and semi-conductors using specific data such as the cost per new drug approved or the cost to continue increasing the number of transistors on a micro-chip.

85%

of scientists say carrying out research is increasingly complex.

Our findings were more encouraging in terms of basic research, the fundamental scientific work carried out to further human knowledge with no specific application in mind. The evidence here suggests that productivity is rising in some countries, when measured by total publications (adjusted for quality, divided by R&D spending). Yet there are reasons to be concerned about the output of basic research too, including the share of papers being retracted due to error or fraud, and the irreproducibility of results by other scientists.

> **"There is so much existing work it's virtually impossible to keep up, and that leads to duplication of effort, which is a serious drag on research productivity."**
>
> *Associate Professor Karthik Kumar, Director, SERC, A*STAR Singapore*

FOUR CRITICAL DRIVERS OF SCIENTIFIC RESEARCH PRODUCTIVITY

Across the full domain of scientific research there are areas where productivity may have plateaued as a technology reaches maturity, and there are hotspots where exciting new discoveries are generating significant amounts of new scientific outputs. However, cutting across these distinctions, the data we have examined point to four critical drivers that impact scientific research productivity both positively and negatively.

- **Increased complexity: Science has become more complex and this is dragging on research productivity.** As science has progressed and grown more complex, larger teams with greater individual specialisations are required. The vast majority of our survey respondents report that carrying out research in their field is increasingly complex and that it is difficult to keep up with the latest literature. There is evidence from multiple sources in our study that this complexity, together with an increasing administrative burden, negatively impacts productivity. However, there is a trade-off, as larger teams provide greater capabilities for making new scientific discoveries.
- **Short-termism: Pressure to produce results in shorter timeframes is weighing on research quality, reducing the focus on research in new fields.** We find that researchers are increasingly facing pressure to publish results in shorter timeframes. Associated with this is a rise in negative impacts on quality such as error, fraud and non-reproducibility. A focus on short term results, as well as short funding cycles, may also be reducing the ability of researchers to focus on new areas of research, without which only incremental innovations can be made.
- **Collaboration and outsourcing: Collaboration is critical, but outsourcing may hinder productivity.** Two ways to increase the capacity or capability of a scientific research team are collaborating with other teams and outsourcing work to a research company. We find mixed results on the effect on research productivity of these two interactions. Cross-organisation collaborations are seen as a key factor in promoting research productivity, including between academia and industry and between countries. Conversely, the rising trend of outsourcing may improve cost-efficiency, but appears to have a negative impact on research productivity.

74%

of scientists say shorter funding cycles have led to less research in unexplored areas.

- **Government support: Governments are generally seen as supportive of R&D, but funding levels could be increased.** Governments are generally seen as supportive of R&D in the countries we examined. However, government funding has increased only very slowly in recent years in many countries after adjusting for inflation and there is concern it may no longer be adequate to fund new "blue sky" projects.

It is worth noting that the rapid development of effective vaccines for COVID-19 models some of the best practices defined by these four areas, including the availability of foundational knowledge from years of basic research; extensive collaboration; and ample public funding.

> **“We need closer collaboration between basic, applied and corporate R&D. There’s a disconnect, with little opportunity for academics and industry to mix.”**
>
> *Philip Jordan, Partner, Innovations, Wellcome Trust, UK*

RECOMMENDATIONS: THE PATH AHEAD.

Our discussions with expert researchers and scientists around the world yielded a number of recommendations for further consideration under three areas of focus. Some of these recommendations were not universally endorsed in our interviews, but are included here to promote discussion.

Strategic goals

- Encourage and support careful collaboration
- Provide greater public guidance and support in key areas, including the government acting as a direct customer for R&D, without reducing public funding through existing channels for wider research programmes
- Develop improved measures of scientific research productivity
- Ensure a balance between investment in blue-sky research and an outcomes-based approach

Funding goals

- Increase the rigor of public research funding by applying the scientific method[2] to allocation decisions
- Avoid short-termism, particularly in projects involving public funding

Process goals

- Promote the wider dissemination of results
- Develop and retain a skilled workforce

The ongoing success of scientific research is a matter of critical, even existential importance. Our study suggests there is work to be done to develop meaningful, widely-accepted productivity metrics that can be used to direct public and private sector funding for optimal outcomes. Meanwhile, the four key drivers of scientific research productivity that we surfaced through our study can serve as key checkpoints for consideration in structuring large-scale projects across the spectrum of scientific research.

> **“When corporate research labs were closed that left a funding gap for applied research that has not been filled.”**
>
> *Tyler Cowen, Professor of Economics, George Mason University, US*

[2] Using scientific principles to test a hypothesis with carefully designed and controlled experiments.

1. SCIENTIFIC RESEARCH: THE ENGINE OF HUMAN PROGRESS

Investments in science, technology, and the innovation they enable are critical drivers of economic growth and human development.[3] The power of research to improve our well-being and extend our lifespans is a defining fact of the modern world.

As India's future first prime minister, Pandit Nehru, declared in 1937, *"it is science alone that can solve the problems of hunger and poverty… The future belongs to those who make friends with science."* In subsequent years, leading economists have developed models that link the impact of technological progress to long-term economic growth.

But what if this great engine of progress slowed, and the march of science was reduced to a crawl? Such a situation would make it more difficult for the world to face challenges ranging from climate change to feeding a growing population.

A body of literature has emerged in recent years to suggest that growth in the productivity of scientific research is indeed slowing, and that analysis inspired this study by Merck KGaA, Darmstadt, Germany and Oxford Economics. We have set out to better understand whether this trend is real, and if so, the countries and industries in which it is most prevalent, as well as the status of productivity across the three stages of the research cycle–basic research, applied research, and development.

We have also sought to understand the key drivers that impact scientific research productivity both positively and negatively. To gain as broad a perspective as possible we used a variety of tools and analysis at a granular level, across the world's most significant countries for R&D spending and the most research-intensive industries.

We find it is impossible to make one conclusive statement about the trajectory of scientific research productivity. There is indeed substantial evidence, based on publicly available data, that scientific research productivity has been in decline for some decades in a number of key industry sectors. But research productivity is a difficult thing to measure, and we found both negative and positive trends across the three phases of the scientific research cycle.[4] The appropriateness of different metrics may change over time and according to the specific research outputs in focus. Many of the scientists we spoke to and who participated in our survey pointed to metrics relying on internal data that suggest an up-tick in productivity, particularly in specific areas of research within a broader industry sector.

Finally, as we explore in further detail in this paper, the concept of how to measure research productivity is itself an important field of study, although there is little consensus on how it is best done. But there is agreement, both broadly and among our survey respondents, that some widely-used metrics, such as the citation-weighted number of publications per researcher or patents per research dollar, can incentivise behaviours that are detrimental to research quality and to the corporate culture of research institutions. And quantity does not equate to quality—the number of patents and publications does not tell us how important or impactful they are.[5]

Huge sums of money are directed to scientific research—much of it generated by the general public through taxes and investments in pension and other funds. Our findings support the need for greater collaboration between providers and recipients of research funding to develop a common framework for measuring to scientific research productivity. A number of early initiatives to investigate research productivity are a promising first step.

In addition to exploring the question of whether scientific research productivity is in decline, we also sought to investigate which factors contribute most to either a decline or an upswing in productivity. We found four key drivers of scientific research productivity, which

[3] G7 Academies Joint Statement, *New economic growth: the role of science, technology, innovation and infrastructure*, 2017
[4] Reflected in previous work authored by a researcher at Merck, KGaA, Darmstadt, Germany, scientist: Betz, *Is the force awakening?*, 2018
[5] There is no standard definition of patent quality, though various frameworks have been developed such as Lanjouw and Schankerman, *Patent quality and research productivity; measuring innovation with multiple indicators*, 2004

we describe in more detail in the next chapter. These are:

- The complexity of research and its effects on productivity;
- The impact of "short-termism" on research productivity and focus;
- Collaboration, outsourcing and productivity;
- The role of government in supporting research.

Our research and analysis point toward some clear issues impeding scientific productivity—but in doing so also suggest some ways forward that may help speed progress in those areas where slowdowns are most evident or problematic.

It is worth noting that our analysis has shown very similar results across all the countries, industries and stages of research that we analysed. This gives us confidence that the problems we have identified are relevant to researchers across a broad sweep of scientific endeavour.

1.1 AIM AND TOOLS OF OUR INVESTIGATION

The aim of our investigation into scientific research productivity has been to:

- Investigate the evidence to understand whether scientific research productivity is in decline;
- Investigate the drivers of scientific research productivity—which factors work to support or hinder productivity.

We approached this investigation with as broad a range of tools as possible, to attempt to capture both qualitatively and quantitatively the important trends in this area.

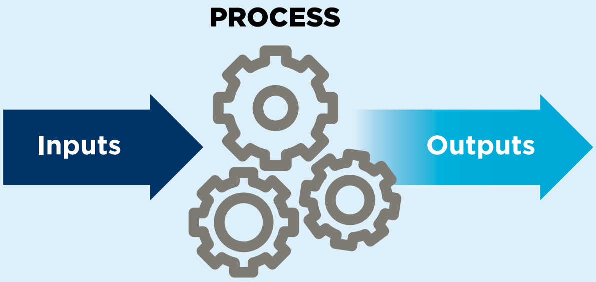
Our research methods included:

1. **A detailed literature review:** We began by analysing the existing literature stretching back decades on the subject of research productivity. Once we constructed an extensive database of papers, having annotated their aims and findings, we were able to group these into areas of recurring themes for further investigation. We split these themes into those that could be assessed qualitatively and those that could be estimated quantitatively.
2. **Stakeholder consultation:** We discussed the long list of themes selected for qualitative review in one-to-one interviews with 25 experts and stakeholders in R&D around the world, including researchers in natural sciences at private companies and universities, researchers in engineering, and economists who have written on the subject of R&D productivity.[6] These interviews helped us to narrow down our long list of themes to those that were felt most strongly by our interviewees to be the most important.
3. **An expert workshop:** We held an online workshop session that brought together eight experts with R&D experience from the US, Europe and China. We asked them to vote on our short list of themes to be explored qualitatively to understand the consensus in this small group of what were the most important areas. We then discussed those areas in greater detail and used the insights to frame our thinking on the survey and analysis to follow.
4. **Statistical analysis:** We have used data from existing public sources to analyse trends in scientific inputs, outputs and productivity in different countries, industries and stages of research.
5. **Econometric modelling:** We investigated the list of themes discovered during literature review and consultations to understand for which there was sufficient data available to conduct an econometric modelling exercise. The aim of this approach was to objectively and quantitatively assess which potential explanatory factors were linked with productivity.
6. **A global survey:** We used the above tools to identify the most important factors that support or hinder scientific research productivity. We then conducted a survey of 3,500 senior scientists, engineers and other R&D workers in seven countries around the world and across five broad sectors of researchers. With this survey, we aimed to collect data on these important factors, as well as provide findings on a broader range of questions.

[6] See Appendix 1: Interview and workshop partners for list of interview partners.

WHAT DO WE MEAN BY SCIENTIFIC RESEARCH PRODUCTIVITY?

Productivity is defined as the relationship of inputs to outputs, for instance how much is produced by a factory compared to how many workers and machines are used in the process.



The concept of productivity is an important one in business and economics, with prominent examples of particular productivity ratios including:

- labour productivity, often measured as GDP per worker or hour worked;
- business productivity, such as the average cost per unit of production, or
- "multi-factor productivity", a macroeconomic concept which reflects the overall efficiency with which capital and labour inputs are used together.

For the purposes of this study, we are interested in the broad concept of scientific research productivity, by which we mean the amount of scientific output created relative to the volume of research inputs used. Inputs are relatively easy to measure—the amount of research funding and the number of researchers are commonly used for this purpose.

The concept of scientific output is a more difficult one to define and measure due to the broad sweep of ideas it encapsulates. In this paper, we explore the idea through measurable scientific outputs such as numbers of academic publications and granted patents, as well as industry-specific measures such as number of new drugs and number of transistors on a microchip, and economy-wide measures such as multi-factor productivity. However, we are limited to publicly available data. Many of our survey respondents noted that other measures, relying on business-specific information, are the most important for their organisation in measuring the return on research investment, such as the number of successful studies or trials per dollar of research budget (65% of respondents) or technology transfer or the commercial success of research ideas (54%).

1.2 SCOPE OF THE STUDY

1.2.1 Definition of scientific research

Scientific R&D is often discussed alongside, and sometimes interchangeably with, the concept of *innovation*. However, scientific R&D is really a component of the broader field of innovation.

The OECD break down innovation into two areas: product innovation (goods or services) and business process innovation, with the latter broken down further into areas such as production, logistics, marketing, ICT, and management / administration.[7]

The OECD also provide a strict definition for what can be considered as R&D activity: it must be aimed at generating new findings; based on original hypotheses; uncertain in its outcome; systematic in its approach, and should lead to results that could potentially be reproduced.[8]

A scientific R&D approach could then potentially be applied to many of the areas of broader innovation described above. A scientific method could be used to develop new products, such as new technologies or materials. It could also be used to test different management or marketing techniques. However, there is much that is done in the field of business innovation that does not involve much in the way of scientific research.

For instance, software innovation can be clearly seen through the explosive popularity growth of social media platforms since the early 2000s. These technological innovations have unquestionably changed life in many ways. With their expansion, some of the most popular social media companies now spend large amounts a year on R&D[9] on improving the service offering and expanding into new areas, but the basic original premise of these platforms often did not require anything in the way of scientific research to start creating an impact.

In this paper, we focus solely on scientific R&D, as a cornerstone of innovation—product innovations such as social media platforms after all would not be possible without the science that developed microchips, the Internet, and the now-ubiquitous smartphone, for instance.

The spectrum of scientific research is divided further into three distinct "stages" as defined by the OECD:[10] basic research, applied research and experimental development.[11]

Basic research	Applied research	Experimental development
OECD definitions		
Experimental or theoretical work undertaken to acquire new knowledge, without any particular use in view.	Original work undertaken to acquire new knowledge directed primarily towards a specific, practical aim.	Work drawing on existing knowledge gained from research directed towards producing new products/processes.
Examples of types of work		
Work to understand how a given class of chemicals react under various conditions.	Attempt to optimise these reactions to produce chemicals with particular useful properties.	Evaluating possible methods for commercially producing these chemicals for use in products.
Organisations typically involved		
Universities and not-for-profit institutions devote large amounts of resources to basic research.	Universities and not-for-profit institutes also focus on applied research, while businesses devote some resources to it.	Experimental development comprises the vast majority of business R&D spending.

[7] OECD, *Oslo manual for collecting, reporting and using data on innovation*, 2018
[8] OECD, *Frascati manual for collecting and reporting data on research and experimental development*, 2015
[9] Bloomberg, *Amazon and Facebook are big spenders on R&D*, 2016
[10] OECD, *Frascati manual*, 2015
[11] The term "experimental development" is also commonly referred to as "translational research", meaning the early-stage development of products, technologies and services building on basic and applied research.

1.2.2 Countries under assessment

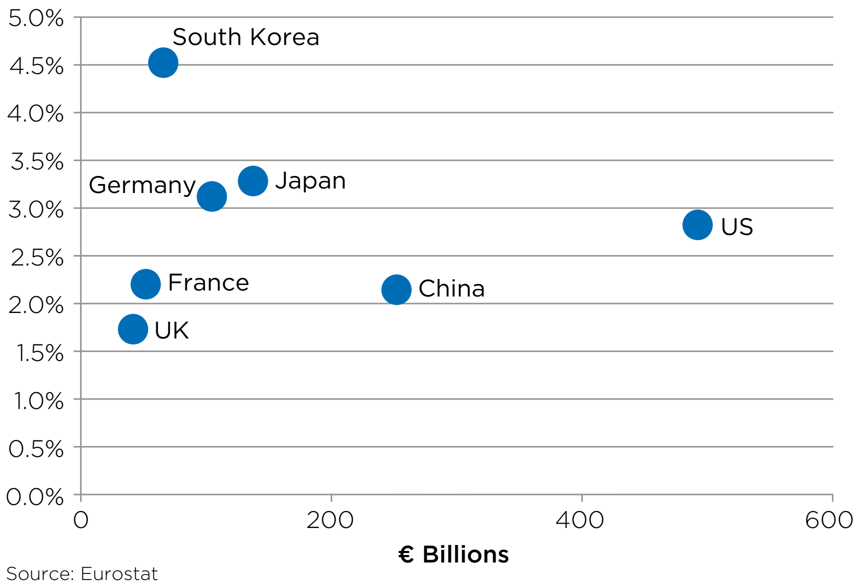
With this work we have sought to gain as global a viewpoint as possible, looking at a broad range of countries in North America, Europe and Asia. While varying degrees of coverage were possible with the different analytical tools we used, our countries of focus are China, France, Germany, Japan, South Korea, the United Kingdom and the United States.

Together, these countries spend far more on R&D than the rest of the world put together—for instance, equivalent to 113% of the total R&D expenditure of OECD countries (as China is not an OECD member). Of these countries, the US spent the most on R&D, at nearly €500m in 2018, followed by China at €250m. The remaining five countries together spent approximately €400m on R&D in 2018 (see Figure 1).

South Korea, however, was the most research-intensive, with R&D expenditure equivalent to 4.5% of GDP, followed by Japan at 3.3%. At the lower end of this spectrum was the UK at 1.7% of GDP and China at 2.1%.

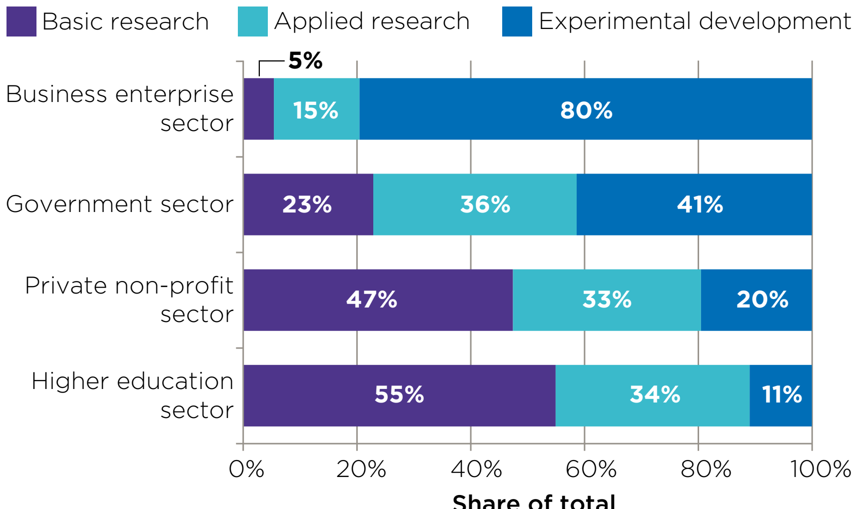
Figure 2 illustrates how the different stages of research are split across the different sectors of the economy, with businesses mostly undertaking experimental development, and universities at the other end of the scale mostly undertaking basic research, as well as a fair amount of applied research.

Fig. 1: Total R&D expenditure by country, billion euros and as a share of GDP, 2018[12]



Source: Eurostat

Fig. 2: Split of type of R&D carried out in each sector on aggregate across countries studied in this report, 2018



Source: Eurostat, Oxford Economics

[12] OECD.stat, *Gross domestic expenditure on R&D by sector of performance and source of funds*

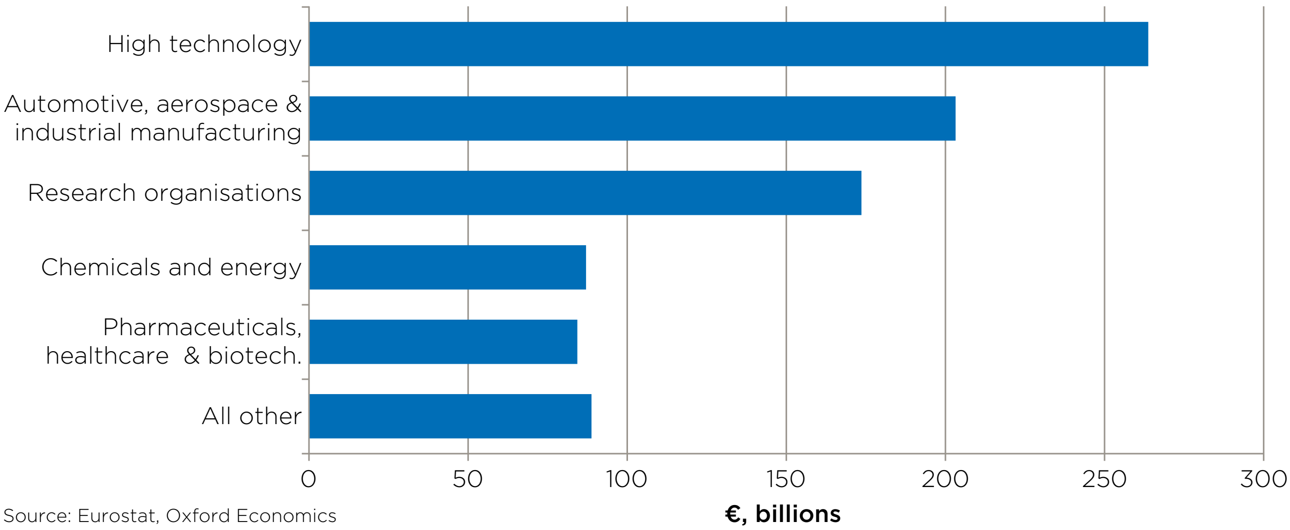
1.2.3 Industries examined

As well as broad country coverage, we also sought to capture trends from a wide spectrum of the industries that perform R&D. We grouped these into the following research areas:

- **Pharmaceuticals, healthcare and biotechnology:** Includes organisations associated with the development and manufacturing of pharmaceuticals; manufacturing of medical equipment, and research into biotechnology.
- **Automotive, aerospace and industrial manufacturing:** Includes organisations associated with the development and manufacturing of all industrial machinery and equipment, including the automotive and aerospace sectors.
- **High technology:** Includes organisations associated with the development and manufacturing of electronic and optical products, electrical equipment, telecommunications and computer and software programming.
- **Chemicals and energy:** Includes organisations associated with the development and manufacture of chemical products, rubber and plastic products, other non-metallic products as well as basic metals. Also includes the electricity, gas, steam, water and sewerage sectors.
- **Research organisations:** In this grouping we include higher education institutes (universities), not-for-profit research institutes and businesses such as contract research organisations that provide outsourced research services.

As far as possible, these sectors (which are aligned with standard industrial classifications) include businesses whose primary activity places them in each category, as well as workers at universities and research institutions whose focus is in each area of R&D. Together, our business sector groupings comprise approximately 85% of total business spending on R&D across our focus countries of China, France, Germany, Japan, South Korea, the United Kingdom and the United States.

Fig. 3: Total business expenditure on R&D by industry groupings across focus countries, 2017[13]



Source: Eurostat, Oxford Economics

[13] "Other" includes spending by research institutions where it has not been possible to disaggregate into area of research. It also consists of other business sectors that do not align with our areas of focus, such as food and tobacco manufacturing, clothing and textile manufacturing, wholesale and retail trade and financial services.

1.1.1 Introducing the Scientific Research Productivity Pulse Check

Following our investigation into the global state of scientific research productivity across all our analytical tools, we identified six quantifiable factors within the four key driver themes discussed above that most strongly influence research productivity and that can be quantified.

We bring together data on these factors, drawing from original information gathered from our survey of 3,500 scientists around the world, in our Scientific Research Productivity Pulse Check. This illustrative tool aims to highlight the extent to which each factor provides support to scientific research productivity across the countries and industries which we have investigated.

2. KEY FINDINGS

This chapter sets out in detail our findings from across our investigation.

Trends in productivity

We begin by highlighting the evidence we have found from the different strands of our research on trends in scientific research productivity. This includes evidence for and against a decline, and the areas where differences are seen or felt.

Drivers of the productivity of scientific research

We then go on to discuss the four main themes that we have identified as critical drivers of scientific research productivity. In two of these areas, we address evidence on the decline of research scientific productivity, while in the remaining two we focus on areas where we found evidence of factors that support research productivity. The core findings our research uncovered were:

- Science has become more complex, and this complexity is dragging on research productivity.
- Pressure to produce results in shorter timeframes is weighing on research quality, reducing the focus on research in new fields.
- Collaboration is critical, but outsourcing may hinder productivity.
- Governments are generally seen as supportive of R&D, but funding levels could be increased.

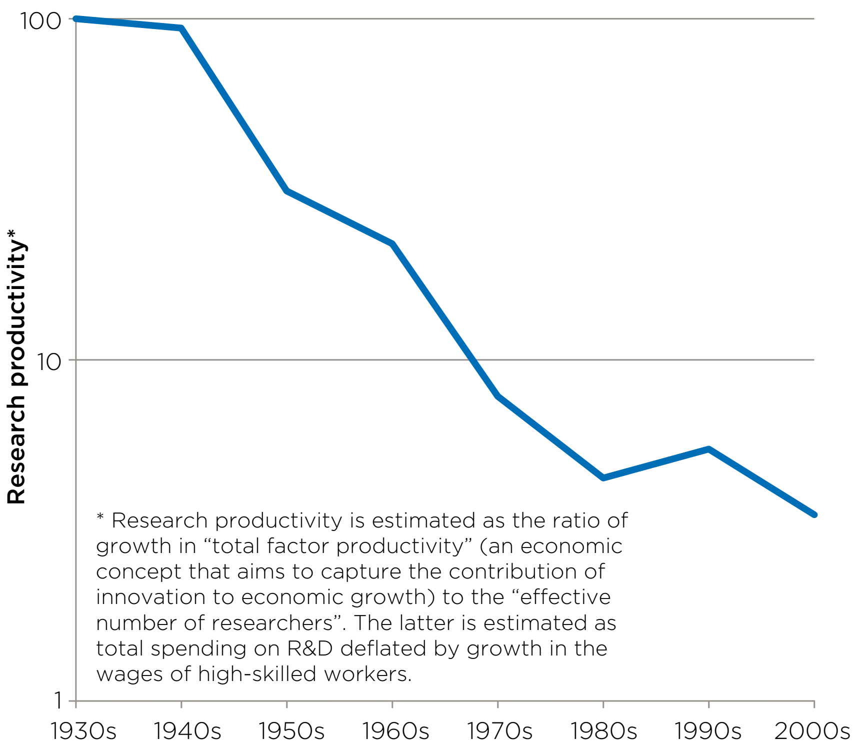
2.1 SCIENTIFIC RESEARCH PRODUCTIVITY IS A COMPLEX ISSUE WITH NO CONCLUSIVE OVERALL TREND

A substantial body of literature concludes that research productivity has declined over the long term, particularly in the US where a lot of these studies are focused. This evidence was the impetus for our study. It includes papers that look at the concept of scientific research productivity at a high level using macroeconomic data, finding robust and wide-ranging evidence that the rate of scientific progress has slowed.[14,15] Potential reasons are also given for why this might be the case, ranging from the broad concept that new ideas are simply getting harder to find, to the more specific notion that rapid innovation has followed the steam, electricity and computer/internet industrial revolutions, before trailing off until the next revolution.[16]

Other studies focus on business-level data, such as returns on R&D spending in the form of revenue, again finding that research productivity has fallen over many decades.[17]

Fig. 4: Long term trend of research productivity in the US

Index (1930 = 100), logarithmic scale



Source: Bloom et al (2019)

[14] Bloom et al, *Are Ideas Getting Harder to Find?*, 2019
[15] Cowen and Southwood, *Is the rate of scientific progress slowing down?*, 2019
[16] Gordon, *Is US economic growth over? Faltering innovation confronts the six headwinds*, 2012
[17] Knott, *Is R&D Getting Harder, or Are Companies Just Getting Worse At It?*, 2017

However, these authors reference potential issues associated with looking at research productivity at this high level, including the lag involved with technological diffusion, where gains in high-level indicators may be based on research carried out a decade before, and the difficulty in measuring recent technological developments that increase consumer welfare but not necessarily consumer spending (such as the free services provided by various websites).

Furthermore, other studies focused on specific industries and countries reach different conclusions on the trend of research productivity.[18] Part of the difficulty is that a wide variety of measures and definitions of productivity are used across the literature, and data availability varies greatly from country to country. In addition, given the extremely broad nature of scientific R&D, as well as the varied reasons for carrying it out (for the sake of scientific curiosity, for commercial gain, to improve peoples' lives etc.), it is difficult to even theoretically design one single measure that accurately and comprehensively captures the concept of research productivity.

There are many other models of measuring productivity, most relying on internal company data that we didn't have access to. For instance, over 50% of our survey respondents said organizations they have worked for over the last 10 years use either technology transfer and commercial success of ideas, or the number of successful outcomes of trials and studies per dollar of research budget, (e.g., number of new drugs, new products, new technologies) to measure return on scientific research investment.

These metrics perhaps explain why 49% of survey respondents believe that the overall return on investment in scientific research had increased over the past 10 years. However, 40% believe that productivity had not changed during that time, and 11% believed it had worsened.

To shed more light on this issue, we have looked at scientific productivity at different stages of the research cycle.

2.1.1 Basic research

The volume of basic research being conducted can be measured most simply by noting the raw number of academic papers being produced. By this measure, the amount of basic research being completed each year has grown steadily over hundreds of years. One estimate[19] is of steady growth of 3.5% a year since the 1600s in the number of peer-reviewed journals. This accelerated to 5%–6% annual growth over the past decade, to reach 33,000 English-language journals publishing somewhere between 1.5 million and 3 million articles a year.

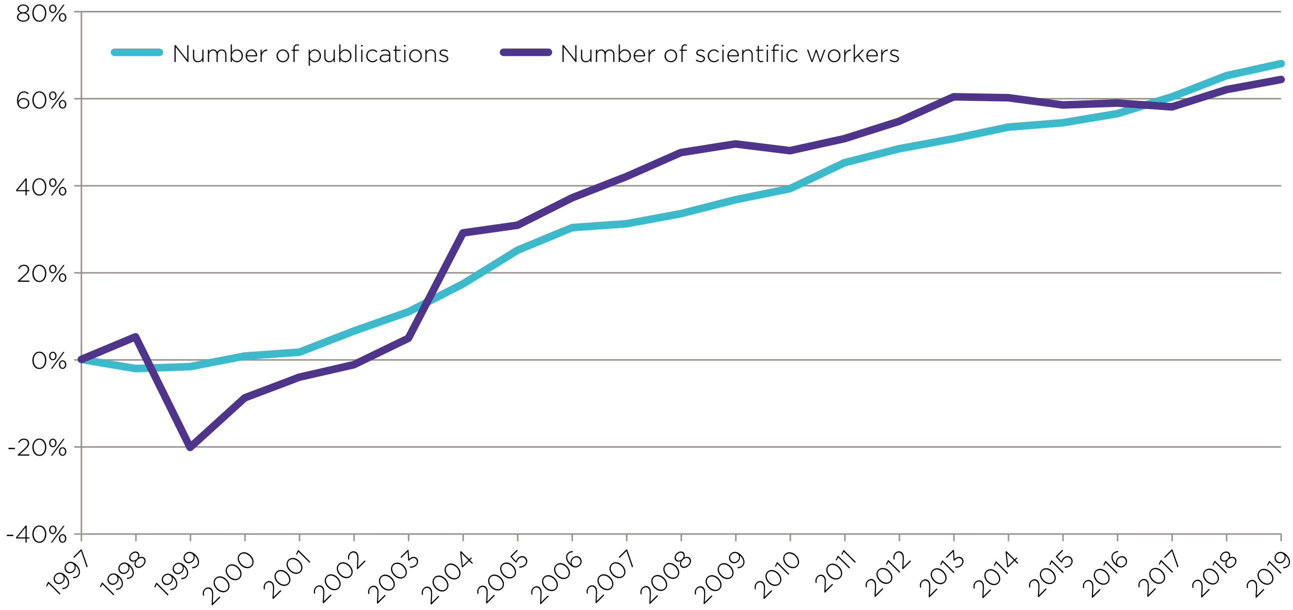
Over the long run, this rise in publication numbers has been closely linked to growth in the number of researchers and in turn, to growth in research spending, as well as the proliferation of journals, making it easier to get lower-impact work published. This is highlighted in the figure below for the US showing the number of scientific workers and publications per year rising largely in step over the past 20 years, with other datasets showing this extending back to at least the early 1980s.[20] This evidence suggests that productivity among academics in terms of the quantity of research produced has remained largely constant over time. Growth in the number of scientific publications and scientific researchers has also been relatively evenly matched in the UK between 2001 and 2018.[21]

In fact, another study[22] looks at the publication patterns of over 40,000 researchers publishing between 1900 and 2015 and finds that the average number of papers produced per researcher over that time has increased, but so has co-authorship. It found that by including only the papers for which the researcher was the lead author, no change in productivity is observed over the century in terms of number of papers produced.

[18] Such as Miyagawa and Ishikawa, *On the Decline of R&D Efficiency*, 2019, which finds a decline in R&D efficiency in the Japanese IT sector, but not the Japanese manufacturing sector.
[19] Johnson et al, *An overview of scientific and scholarly publishing*, 2018
[20] Figure 9, Johnson et al, *An overview of scientific and scholarly publishing*, 2018
[21] Oxford Economics analysis of Office for National Statistics employment by scientific professionals occupation data and ScimagoJR/Scopus data on number of publications in scientific subjects.
[22] Fanelli and Lariviere, *Researchers' Individual Publication Rate Has Not Increased in a Century*, 2016

Fig. 5: Numbers of researchers and publications, US[23]

Change since 1997



Source: US Bureau of Labor Statistics, ScimagoJR, Oxford Economics

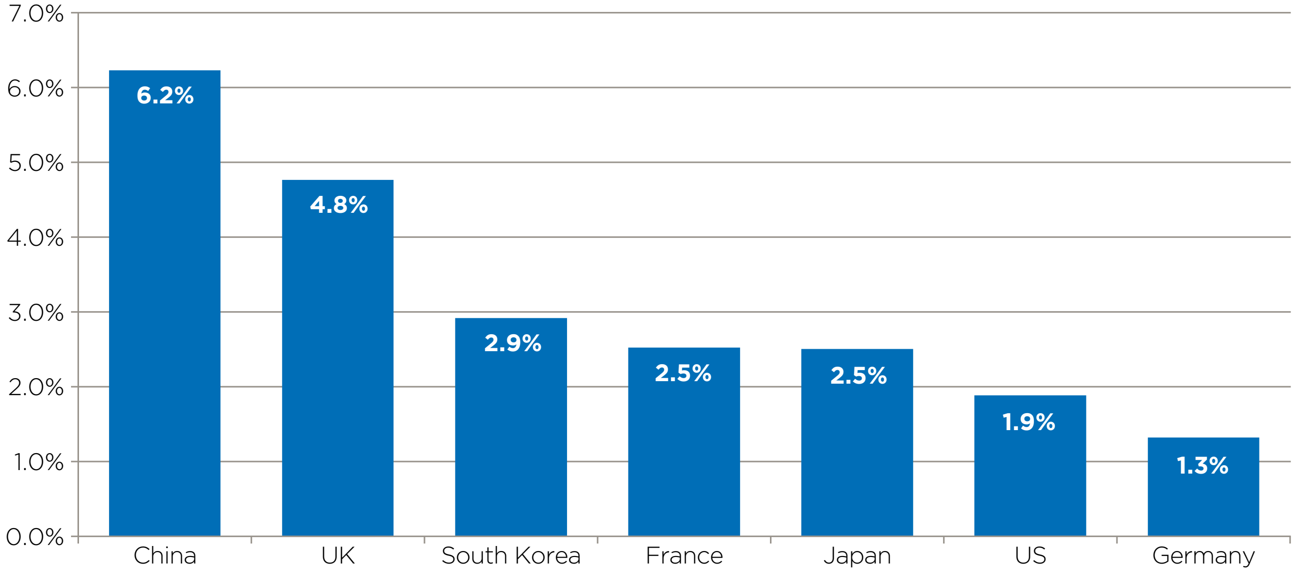
These studies consider output in the simplest terms, examining just the number of publications. A more nuanced approach is to adjust for quality, for instance by using the average number of citations per paper, and adjust for the amount of funding. We find evidence that the productivity of basic research as measured in this way has climbed over the past 20 years across our focus countries after adjusting for inflation.[24]

Although on the surface these trends appear to be positive, there is also much evidence that a rising tide of lower-quality work is being published, a form of "research inflation." This is partly linked to the increase in the number of journals, and changes in publishing models—new open access journals mean more can get published, for a publication fee. Poor quality studies are often characterised by the non-reproducibility of results or a rising share of retractions through error and fraud. These issues are discussed at greater length in section 2.2.1. It should also be noted that more output, in terms of number of publications, does not equate to greater impact. More complex research can result in fewer papers per research dollar compared to narrower programmes, but can lay a foundation for higher levels of innovation. These issues have been broadly recognised by the scientific community, and by governments. China's Ministry of Science and Technology, for example, introduced two new policies in 2020 aimed at addressing issues related to low-quality and fraudulent research.[25]

[23] Publication figures taken from Scimago Journal & County Rank based on Scopus data, for subjects covering the broad areas of biological, chemical and physical sciences. Scientific worker employment figures taken from the Bureau of Labor Statistics, covering occupations in life and physical sciences.
[24] Inflation adjustment is done using national implied GDP deflators (following DiMasi et al, *Innovation in the pharmaceutical industry: new estimates of R&D costs*, 2016).
[25] Zhang and Sivertson, *The New Research Assessment Reform in China and Its Implementation*, 2020

Fig. 6: Change in productivity of basic research by country (total country citation-weighted publications per million euros of R&D activity performed by higher education institutes)[26]

Average annual change, constant prices, 2001-2018



Source: SciVal / Scopus, Eurostat, Oxford Economics

[26] Spending is allocated to countries based on the location of the business units performing the R&D activity, expressed in constant prices using national GDP deflators (following DiMasi et al, *Innovation in the pharmaceutical industry: new estimates of R&D costs*, 2016). Publications are assigned to countries based on the location of the institution. This may not be a perfect allocation for publications by multinational corporations: however, corporate publications make up approximately 5% or less of total publications in each of our seven focus countries.

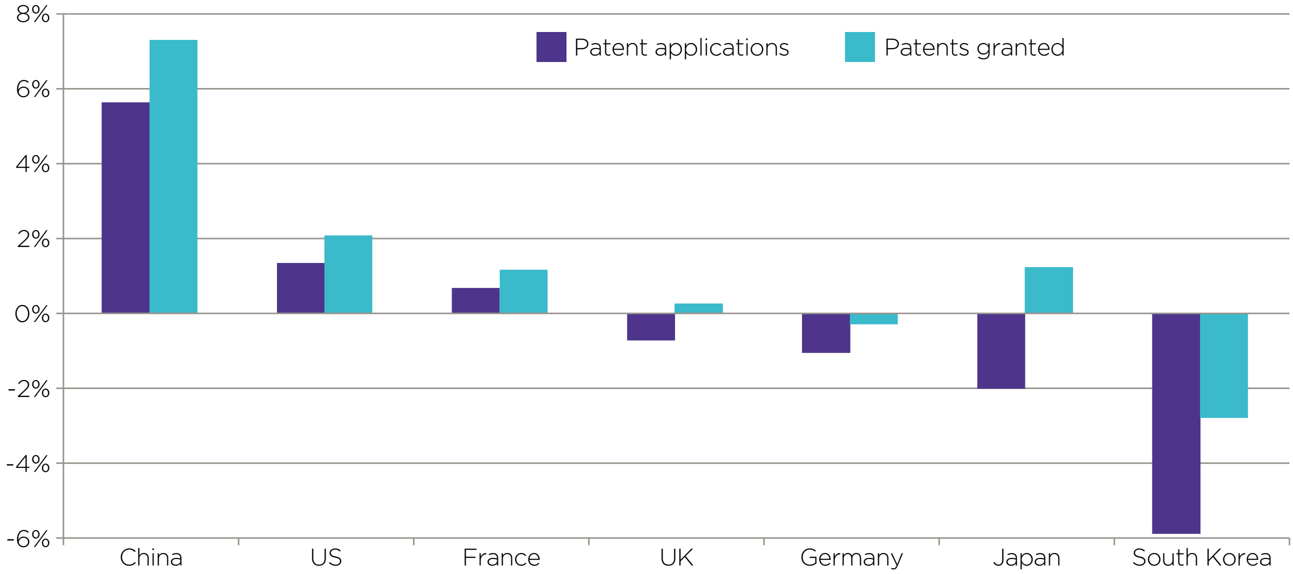
2.1.2 Applied research and experimental development

Looking at aggregate figures on patents and R&D spending by businesses offers a very high-level overview of productivity in applied research and experimental development. For most of our countries of focus, the number of patent applications and patents granted per million euros of R&D spending was flat or declined between 2003 and 2018. However, it should be noted that, similar to looking at the raw number of academic publications for basic research, this approach makes no account for the quality, impact or usefulness of patents produced, so is also an imperfect measure of research productivity.

A notable exception to the downward trend in productivity in applied research and experimental development is China, which saw growth in the productivity of patent applications and a larger increase in the productivity of patents granted: this is due to a rising share of patent applications from China being successfully granted. Similarly, Japan saw growth in the productivity of patents granted: this may be due to Japanese firms shifting focus from the quantity of patents filed to concentrating on the quality and usefulness of patent applications.[27]

Fig. 7: Change in productivity of applied research/experimental development by country, as measured by total patent applications and patent grants per million euros of business R&D spending[28]

Average annual change, constant prices, 2003-2018



Source: WIPO, Eurostat, Oxford Economics

[27] Clarivate, *How pursuing patents in Japan has evolved over the past decade*, 2020
[28] The selected time period is based on the period for which data for all selected countries are available. Spending data notes as per previous figure. Patents are allocated to countries based on the country of residence of the first named applicant, which can be a multi-national corporation. As such, this will not be a perfect allocation and should be considered more illustrative than definitive.

TRENDS IN RESEARCH PRODUCTIVITY BY INDUSTRY

In this box we provide evidence on the trends in scientific productivity seen across a few different industries: electronics, pharmaceuticals and automotive. In the first of these two in particular, there is evidence of a decline in scientific productivity over many decades. This evidence is based on publicly available data—measures that use internal company data may reach different conclusions.

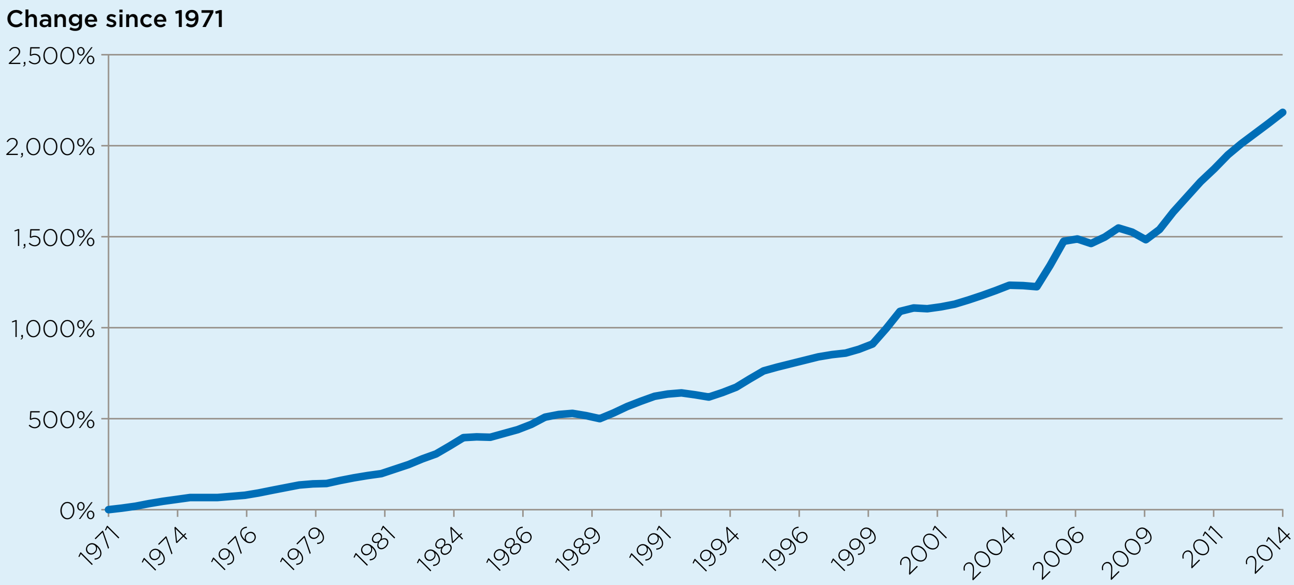
Electronics

Moore's Law states that the number of transistors on a computer chip doubles approximately every two years—equivalent to growth of approximately 35% a year. If research productivity remained constant, it could be argued that amount of R&D investment required to continue this doubling should remain constant.

That has not proven true, however: the number of researchers required to double chip density today is more than 18 times the size of the number required in the 1970s. This is shown in the figure below, suggesting research productivity in this area has been declining by 7% a year,[29] although it should be noted that not all of these employees will be working on semi-conductors.

Other research confirms the requirement for additional R&D resources for newer generations of electronics technology, with semi-conductor manufacturers and foundries reporting cost increases of 35% from one technology to the next, and "fabless" semi-conductor firms facing cost increases of 60% on next generation processes.[30]

Fig. 8: Growth in estimated number of researchers in US semi-conductor industry[31]



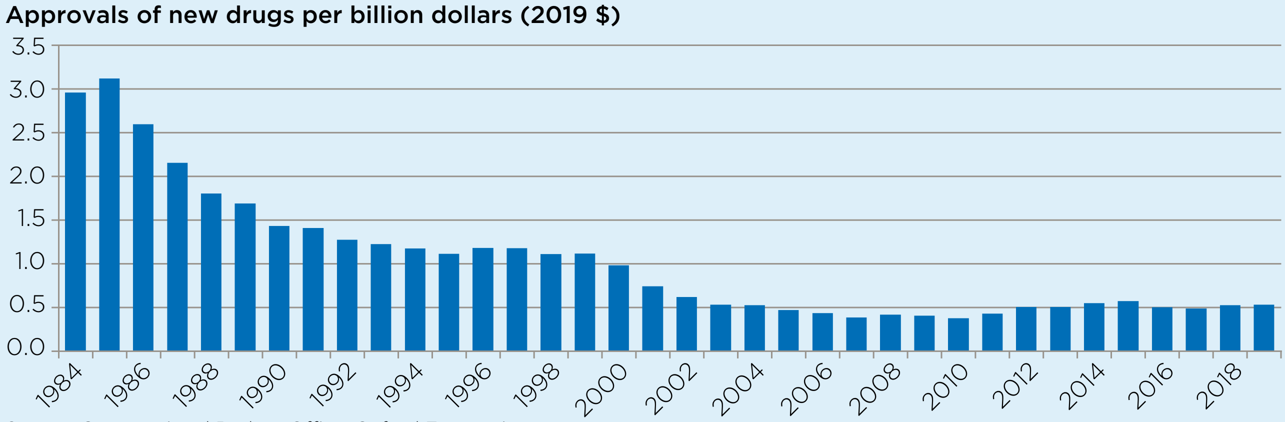
Source: Bloom et. al. (2019)

[29] Bloom et al, *Are Ideas Getting Harder to Find?*, 2019
[30] AlixPartners, *When the Chips Are Down: The Need for Greater R&D Efficiency in the Semiconductor Industry*, 2013. "Fabless" semi-conductor companies are those that focus on design and outsource manufacturing.
[31] Number of researchers is estimated by taking total R&D expenditures from semi-conductor firms Intel, Fairchild, National Semiconductor, Texas Instruments, Motorola and over two dozen others, and deflating by the average wage of high-skilled workers.

Pharmaceuticals

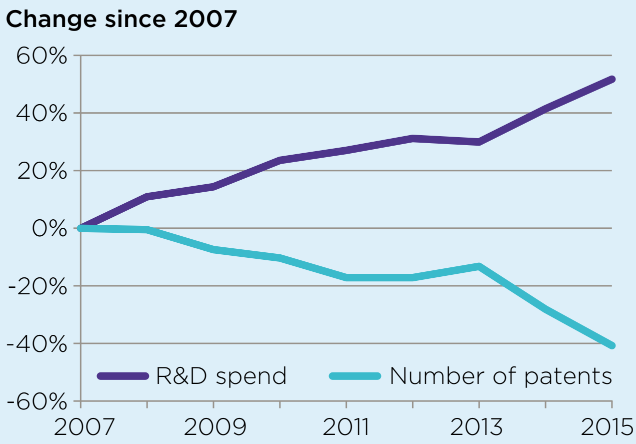
Measuring R&D productivity in the pharmaceutical sector is difficult for many reasons, not least the time lag between R&D investment and registration of new molecular entities (NMEs) or patents, as well as the increasing trend towards in-licensing, development alliances and acquisitions, making it hard to assess exact R&D spend per NME. Nevertheless, most studies that focus on NMEs or patents find that the cost of developing new drugs has been steadily increasing for decades[32]—a trend that has been dubbed "Eroom's Law" (i.e. Moore's Law written backwards). In fact, between the 1950s and the early 2010s, the number of drug approvals per inflation-adjusted dollar invested in R&D has halved every nine years.[33] The last decade, however, has shown signs of a plateauing of this trend, with the number of new molecular entities approved per billion dollars of research spending holding roughly steady[34] (see figure below).

Fig. 9: New molecular entities (five year moving average) approved by the FDA per billion dollars of R&D spending by PhRMA members



Source: Congressional Budget Office, Oxford Economics

Fig. 10: R&D investment and patenting trends for pharmaceutical and biotech companies



Source: Oxford Economics

This is due to a sustained uptick since 2012 in the average number of new drugs approved each year by the US Federal Drug Administration (FDA) coinciding with a commensurate uptick of in-year R&D spending by members of the Pharmaceutical Research and Manufacturers of America (PhRMA) trade association.

As well as the number of drugs being approved, we can also look at productivity in terms of the number of patents filed compared to the amount of R&D spending. At a sample of 148 of the world's highest-R&D-spending pharma and biotech companies, total research expenditure increased notably between 2007 and 2015, while the number of patents filed declined, suggesting an increasing cost per patent in the industry.[35]

[32] DiMasi et al, *Innovation in the pharmaceutical industry: new estimates of R&D costs*, 2016
[33] Boston Consulting Group, *Unlocking Productivity in Biopharmaceutical R&D*, 2016
[34] US Congressional Budget Office, *Research and Development in the Pharmaceutical Industry*, April 2021
[35] European Commission, *The 2019 EU Industrial R&D Investment Scoreboard*, Figure 5.6

The above metrics are based on business data, but focus on the largest companies in the industry rather than also including smaller firms. While the largest companies account for the majority of R&D spending, smaller companies are responsible for a rising share of new drug discoveries,[36] and there is mixed opinion on whether smaller or larger pharmaceutical firms are more productive in terms of number of new NMEs per research dollar.[37,38,39]

The above evidence suggests that it has become more expensive over the decades to produce new drugs. As we have noted, there are many other measures of productivity that we have not been able to consider as they rely on internal data. There are also other metrics using publicly available data but focused on impact rather than productivity: for instance, each new drug may be saving or improving the quality of more years of life than previously.

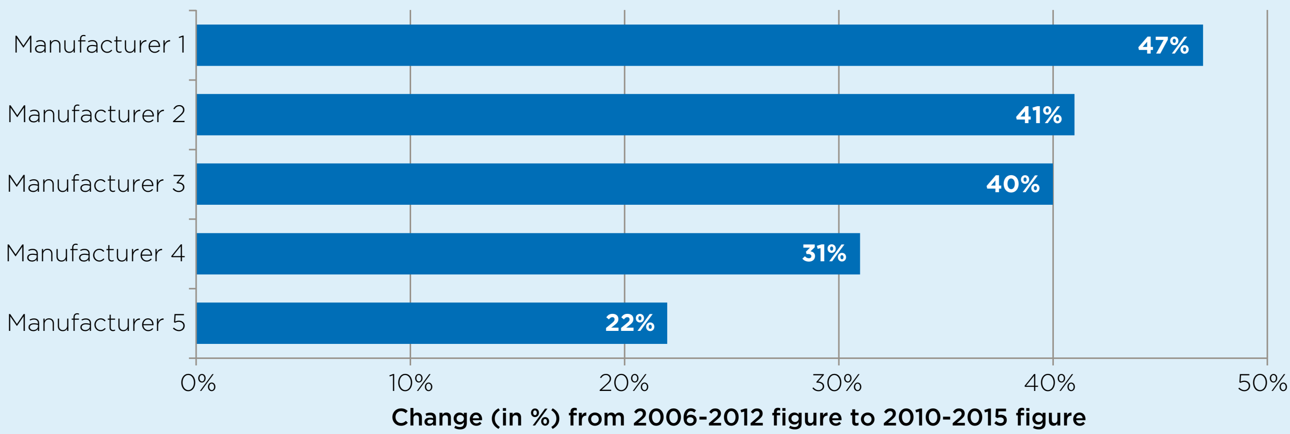
Automotive

Similarly, R&D efficiency in the automotive sector appears to have declined in recent years. One paper[40] links R&D spending to research outputs in terms of "full vehicle equivalents" (FVE). One FVE is equivalent to developing the first version of a new automobile model from start to finish, and other units of research are measured as a fraction of that based on research spending levels. For instance, an estate car / wagon version of a lead vehicle is 0.2 FVE.

This research shows that across five different car manufacturers, R&D costs per FVE increased significantly between 2006-2012 and 2010-2015 (see figure below). One reason given for this is heavy investment in early-stage technologies such as electric vehicles and autonomous driving systems.

There are also signs that research spending in the automotive sector is having less of an impact on measures of business output. According to one study, carmakers' R&D costs have risen significantly as they develop electric, connected and autonomous vehicles, such that research spending has outpaced sales growth in Europe and North America even with continuous growth in production volumes and revenues since 2011.[41]

Fig. 11: Increase in R&D spend per full vehicle equivalent from 2006-2012 to 2010-2015



Source: Boston Consulting Group (2017)

[36] HBM Partners, *New Drug Approval Report*, 2018. Finds that 63% of NMEs approved by the FDA in 2018 were initially developed by small biopharma companies, compared with only 31% in 2009.
[37] DiMasi et al, R&D Costs, *Innovative Output and Firm Size in the Pharmaceutical Industry*,1995. Finds that R&D cost per new drug fall as the size of the firm increases.
[38] Marshke et al, *Relation of Firm Size to R&D Productivity*, 2004. Finds fewer new drugs per R&D dollar decline as the size of the firm increases (i.e. gets more expensive).
[39] A 2012 *review* of the evidence by the UK Office for Health Economics concludes that "*results of research on the impact of firm size on R&D productivity and R&D costs are mixed. It remains unclear whether R&D productivity is greater for smaller companies than for traditional "big pharma"* .
[40] Boston Consulting Group, *How A New Metric Can Boost Auto-makers Productivity*, 2017
[41] Strategy&, *Digital automotive R&D*, 2020

2.2 GREATER COMPLEXITY, LOWER PRODUCTIVITY

2.2.1 Research is becoming increasingly complex, requiring larger teams

In 1675, Isaac Newton famously wrote *"If I have seen further, it is by standing on the shoulders of giants."*[42] This aphorism is often used to symbolise scientific advancement—it is the nature of scientific research to build on previously-discovered knowledge and work carried out by predecessors.

As research progresses it becomes more complex, almost by definition. Ideas are refined, and new processes and equipment are developed to allow for ever-more-detailed study of the natural sciences, and more precise engineering processes. A good example of this phenomenon is the electronics industry, where large amounts of research effort have been expended over the last 50 years. In 1971, Intel released the first commercially produced microprocessor (the "4004"), which contained 2,250 transistors. By 2020, Apple released a chip (the "M1"), containing 16 billion transistors. Clearly, advanced design and manufacturing techniques have evolved rapidly as a result of huge investments in R&D and significant advances in scientific understanding.

This same pattern appears to repeat across the full range of the scientific research environment. In our survey of 3,500 senior researchers around the world, **85% of respondents agreed that carrying out scientific research in their field is increasingly complex**, including 27% who strongly agreed with the statement. Furthermore, researchers in experimental development were more likely to strongly agree about this rising complexity (31%, compared to 25% across basic and applied research), potentially highlighting how complexity increases further as an innovation proceeds up the technology readiness levels.[43]

As complexity grows, expertise in a larger number of very specialised skillsets becomes necessary. In microprocessor development, for example, much greater specialisation is now required in terms of chip design, materials science, software and fabrication than at the dawn of the industry. This trend brings its own challenges—**36% of our respondents noted that increased specialisation and larger teams were a substantial barrier to productivity at their organisation**, with 34% saying that organisational structure and management issues were significant challenges.

This need for greater specialization, collaboration among specialities and larger teams is evident in data on patents: between 1985 and 1999, the average number of inventors cited per patent rose steadily in the US from 1.7 in 1975 to 2.3 in 1999. In addition, the likelihood of an innovator changing technical fields between patent applications has fallen, as deeper technical expertise makes it more difficult to switch.[44] Of course, having bigger teams with a wider range of technical expertise makes it possible to continue expanding the frontier of scientific knowledge, but it is a trade-off between gaining that extra capability and the administrative overheads that are imposed.

To reflect this reality, we built an econometric model based on a database of firm-level data for the US, UK and Germany. We found, all else being equal, **that the higher a firm's total assets, the lower its scientific productivity**.[45] These econometric findings are consistent with some of the existing literature, such as a study that looked at semi-conductor teams at six companies and found that productivity fell as the size of teams increased.[46]

[42] American Scientist, *On the shoulders of giants*
[43] Technology readiness levels are a method for estimating the maturity of technologies, developed at NASA during the 1970s and more broadly applied since then.
[44] Jones, *The Burden of Knowledge and the Death of the Renaissance Man: Is Innovation Getting Harder?*, 2009
[45] Scientific productivity was defined here as the number of patents granted per million dollars of R&D spending.
[46] McKinsey & Co, *By the numbers: R&D productivity in the semiconductor industry*, 2014

Further, more complex operations may also require teams to be located across different campuses, time zones, or even continents: semi-conductor development teams that spanned three sites were found to be up to 20% less productive than those focused only at one site.[47]

While much of the evidence points to an inverse relationship between size and productivity, some scholars suggest more of a "U-shaped" relationship,[48] i.e. both small and large firms have a competitive advantage over moderately-sized ones in terms of R&D productivity. This may be because small firms can react quickly to changes in market needs, while large firms have abundant R&D resources that may span a number of specialisations and because they can spread the cost over a greater manufacturing output, whereas those in the middle possess none of these advantages.

2.2.2 Low-hanging fruit already picked in some fields

Given that existing research builds on centuries of existing work, the accumulating stock of knowledge means that the innovation frontier is constantly pushed further away. This is referred to in some of the literature as the "low-hanging fruit" having been already picked.[49] Of course, at the time these discoveries would likely not have appeared easy.

However, we have heard from our interviews with R&D professionals that even within the timespan of individual careers, work to progress the field that would previously have taken only a few researchers now requires larger teams.

In some areas of research, this may mean that successive generations of innovators face an increasing burden to acquire previously generated knowledge and indeed **71% of our survey respondents report that it is difficult to keep up with the latest research in their field.** This results in a need to spend more studying to reach full productive potential, in part as shown by lengthening duration of doctorates. For instance, one paper[50] finds that the average age of the researcher at their "first innovation" rose from approximately 30.6 in 1985 to 31.4 in 1999, and the age at which Nobel Prize winners create their "great achievement" has been rising at a rate of 5.8 years per century.

While this may simply be an unavoidable consequence of the process of scientific discovery, the question is whether or not this poses a problem for R&D productivity. Many of our survey respondents suggest that it is: **a notable third (34%) believed that natural limits to discovery and the easiest targets already having been reached were significant barriers to research productivity in their industry.** The number of respondents who consider this a challenge is slightly higher among respondents from basic research (37%, vs. 32% in applied research and 27% in experimental development).

[47] Ibid.
[48] Tsai, *R&D productivity and firm size: a nonlinear examination*, 2004
[49] Cowen, *The Great Stagnation: How America Ate All The Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel Better*, 2011
[50] Jones, *The Burden of Knowledge and the Death of the Renaissance Man: Is Innovation Getting Harder?*, 2009

WAITING ON THE DIGITAL BOOM: The impact of information technology on scientific productivity

The economist Robert Solow said in 1987 that "the computer age is everywhere except the productivity statistics". While information technology has since made an enormous impact across the global economy, Solow's point remains relevant: new technologies frequently take some time to create measurable, real-life outputs such as productivity. One widely-held theory about this phenomenon is that it simply takes time for society to sort through the many combinations and permutations of new technologies and business models before seeing results.[51]

Now a new generation of digital technologies, including artificial intelligence and robotics, has seized the spotlight[52]—without yet delivering major impacts on economic or scientific research productivity. In fact, many of our survey respondents are disappointed by payoffs to date, with 34% saying AI has improved productivity less than expected. (A similar number say they have been disappointed by productivity payoffs in robotics and advanced analytics.)

Getting value from technology depends on more than buying the tools—strategy, talent, and processes built to support those tools matter, too. That may be one reason why AI appears to be showing more value in high-technology sectors, where roughly one-quarter of survey respondents report an AI-related improvement to research productivity, while the technology is seen as less useful across the broader economy, with only 17% of other respondents reporting a substantial impact. These trends also are evident for robotics, with respondents from the industrial and automotive sector more likely to report a substantial productivity impact.

The value delivered by other new technologies varies by sector, too. Within the healthcare and biotechnology industries, for example, about one-third report that powerful tools such as CRISPR (a technology that can be used to edit genes) or DNA sequencing have had a substantial impact on improving research productivity; over one-quarter say the same for better screening and testing capabilities.

Other Oxford Economics research shows that AI and AI-enabled technologies will represent a larger share of digital investments for companies across sectors in the years ahead, and we have seen that early benefits accrue more to particular functions and industries than others. Already, though, these tools are critical to effective data-sharing, collaboration, and analysis—important levers for improving productivity that should have a spillover effect on scientific research. Measuring the value from emerging technologies is difficult, but based on the history of information technology and our research in this area, we expect digital transformation to have an increasingly large impact on scientific productivity in years to come.

[51] The Economist, *The Onrushing Wave*, 2014
[52] Forbes, *The Top 10 Artificial Intelligence Trends Everyone Should Be Watching In 2020*, 2020

2.3 THE PRODUCTIVITY PRESSURE-COOKER: HOW SHORT-TERMISM AND PUSH FOR RAPID RESULTS AFFECTS RESEARCH PRODUCTIVITY

2.3.1 There is greater pressure to produce results more quickly, which may be dragging down research quality

We found a substantial amount of evidence of factors that may be weighing on productivity in basic research which we set out here, across aspects such as:

- researchers facing pressure to publish results, particularly in shorter timeframes;
- ways in which this pressure is being dealt with by researchers;
- the effect that the wave of publications is having on the production of quality new work;
- a rising trend of issues with new work, such as fraud, error and non-reproducibility of results.

Pressure to publish

Much has been written about the pressure that academics face to maintain their annual rate of publications—so-called "publish or perish." One survey[53] of research-oriented US business schools found that 94% of professors experience pressure to publish in peer-reviewed journals, and in particular to publish in the top tier of journals. ("We really only receive credit for publishing in A-grade journals", and publication in less-than-A-grade journals "doesn't really count for much."[54])

Three quarters (73%) of our respondents agreed that the pressure to produce results or publish papers had increased over the past 10 years, with 28% strongly agreeing with this notion. In addition, **37% agreed that the pressure to produce results within shortening timeframes is a significant barrier to research productivity** in their industry.

This pressure to publish more research, more quickly, could provide incentives for researchers to try to "game" the system. An often-cited example of one way that researchers can increase their publication count is through the practice of "salami slicing" their body of work into smaller components and publishing findings separately. This has the effect of reducing the potential impact of each paper, as each paper contains less comprehensive content. A review of journal guidelines in 2020[55] found that only 13% of 200 medical journals had policies that guard against both duplicate and salami sliced papers, suggesting there is scope for authors to pursue these practices. However, there is limited empirical evidence that this is taking place.

> **"If a scientist wanting to be hired wasn't suggesting building a big lab and generating cash flow they wouldn't be hired – decisions like these are driven by financial incentives, not research productivity incentives."**
>
> ***Ian Billick PhD, Executive Director, Rocky Mountain Biological Laboratory***

Pressure to produce research findings more quickly may also offer researchers less time to confirm they are up to speed with the latest research, especially given the tremendous rise in publication numbers as described previously. Indeed, **nearly three quarters (71%) of our respondents reported that it is difficult** to keep up with the sheer volume of new research in their field. As a result, we have heard from speaking with researchers that it is common to use search engines for papers on a specific topic, rather than leafing through physical journals. While it may be impossible to quantitatively measure the impact of this trend, anecdotally it is suggested that this approach may lead to fewer "serendipitous" sparks of inspiration by reading seemingly unrelated papers.

[53] Miller et al, *Publish or perish: academic life as management faculty live it*, 2011
[54] Ibid.
[55] Ding et al, *Duplicate and salami publication: a prevalence study of journal policies*, 2020

Rising trend of quality issues

This pressure may also be affecting quality, with **59% in our survey believing that too much low-quality research is being produced.**

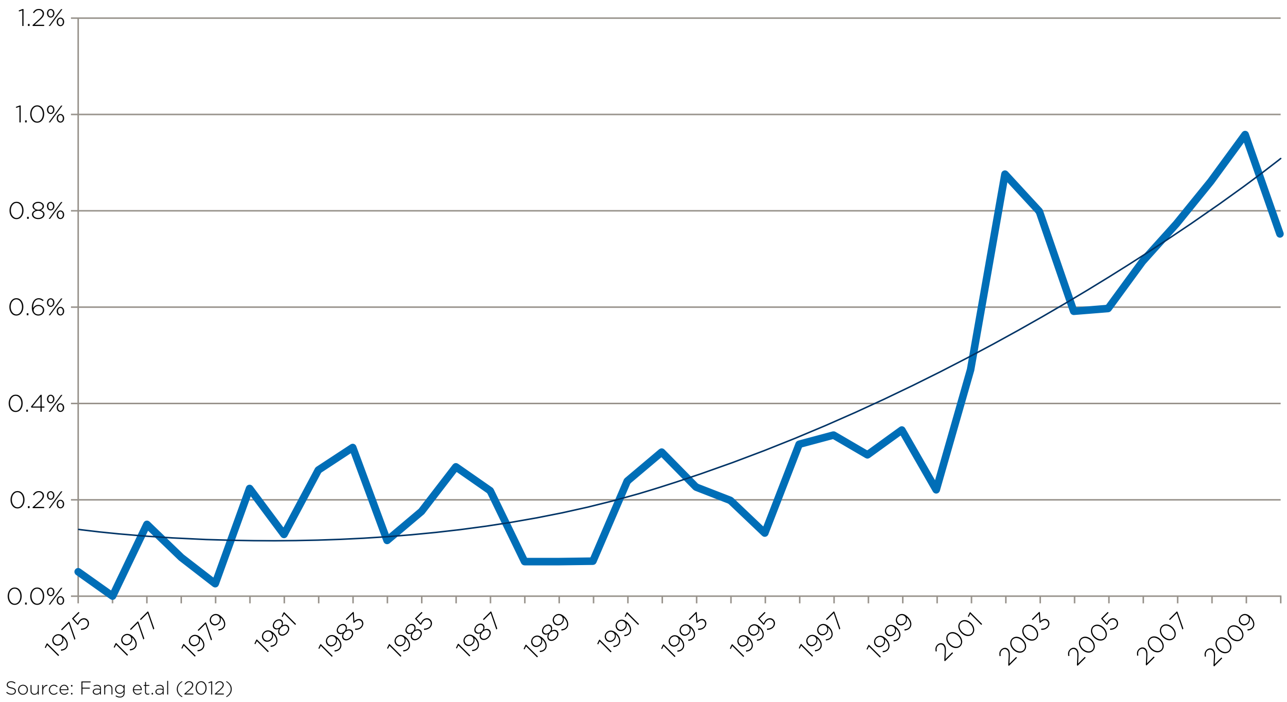
The number of papers being retracted because of error, inability to reproduce results, plagiarism and fraud reflects a general decline in overall quality. One review[56] looked at every retracted English-language biomedical publication indexed on PubMed between 2000 and 2010. It found the number of retractions rose to approximately 180 per year by 2009 from less than 10 per year in 2000.

Another study[57] found that the most common reason for retraction was suspected or actual fraud. The number of papers retracted for this reason was roughly double the number retracted for error, plagiarism or being a duplicate finding, and this figure rose markedly between 1975 and 2005. It should be noted, however, that software is increasingly effective in detecting plagiarism and as such, we may see plagiarism decline as a reason for retractions in the future.

According to a 2016 survey by *Nature*,[58] 52% of surveyed researchers agreed that there is a significant crisis in reproducibility, and a further 38% believed there is a slight crisis. The majority of scientists have failed to reproduce an experiment, with particularly high failure rates in chemistry and biology.

One study[59] in the specific field of oncology and haematology showed that the results of only 11% of 53 "landmark" papers could be reproduced. A meta-analysis of existing studies[60] found that the total prevalence of irreproducible pre-clinical research exceeds 50%, meaning approximately $28 billion a year is spent on irreproducible pre-clinical research in the US alone.

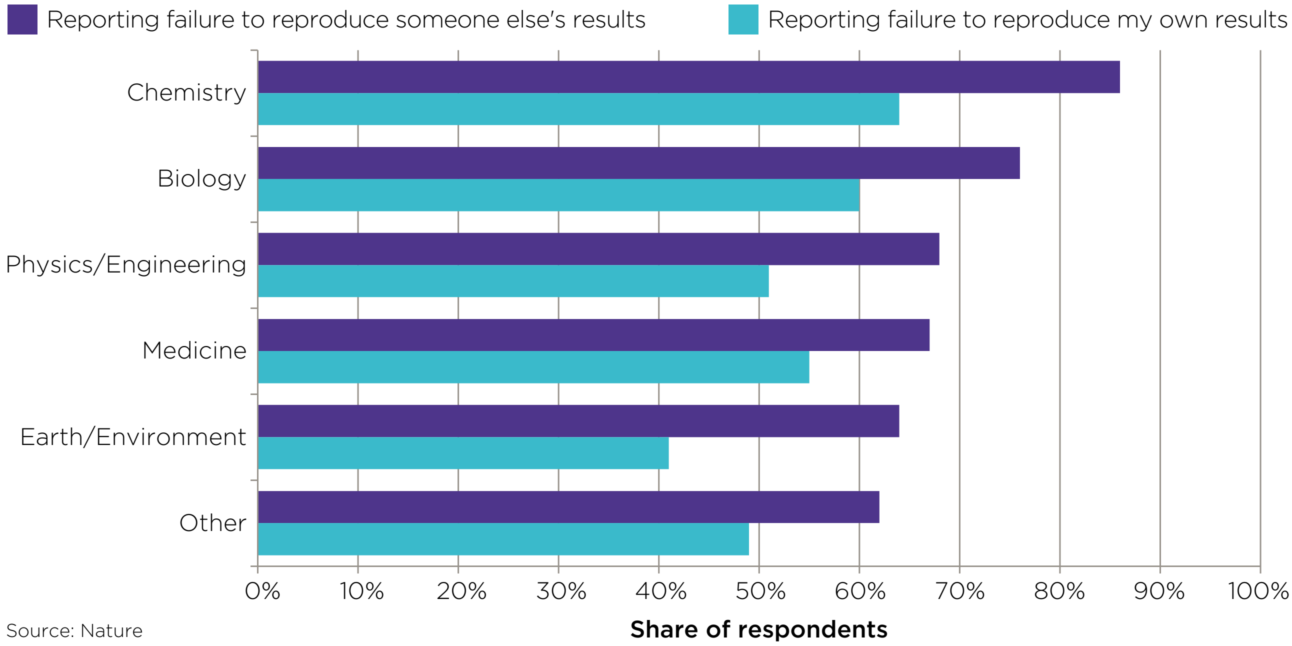
Fig. 12: Share of articles retracted for suspected/actual fraud in biomedical and life sciences articles indexed by PubMed



Source: Fang et.al (2012)

[56] Steen, *Is the incidence of research fraud increasing?*, 2010
[57] Fang et al, *Misconduct accounts for the majority of retracted scientific publications*, 2012
[58] Nature, *1,500 scientists lift the lid on reproducibility*, 2016
[59] Nature, *Raise standards for preclinical cancer research*, 2012
[60] Freedman et al, *The Economics of Reproducibility in Preclinical Research*, 2015

Fig. 13: Scientists reporting failure to reproduce an experiment's results



Source: Nature

2.3.2 "Short-termism" may also be holding back research quality and productivity

According to one study[61] a corporate focus on short-term results is rising. This "short-termism" has implications for research outcomes: firms more focused on the long-term were found to have spent almost 50% more on R&D between 2001 and 2014 than shorter-term companies, and continued to grow research spending even through the global financial crisis. While this does not address the productivity of research, we have heard anecdotally that increasing short-termism at firms and third-party funders means that research projects are not always able to achieve their full potential and may be cut off before the most impactful results are reached.

Our survey respondents support this view: **59% felt that pressure from management to produce results as soon as possible was detrimental to scientific research productivity.** This is also not limited to the corporate sector: for instance, we have heard anecdotally from interviewees in China that not only do the Chinese government's Five-Year Plans already limit the scope of many research projects, but that updates are also required each year with the scope for funding to be cut short. Other studies[62] point specifically to short-term mindsets as the cause of declining R&D productivity. Potential reasons given for this as a driver of declining productivity include the declining tenure of managers and a preference among investors for short-term projects that offer more certain but lower returns than more risky, longer-term projects with potentially much greater returns.

> **" In many companies, senior managers hold their positions typically for around 2 or 3 years, so whatever initiative they invest in has to deliver over that timeframe. "**
>
> *Dirk Voelkel, VP, Innovation, Cytiva*

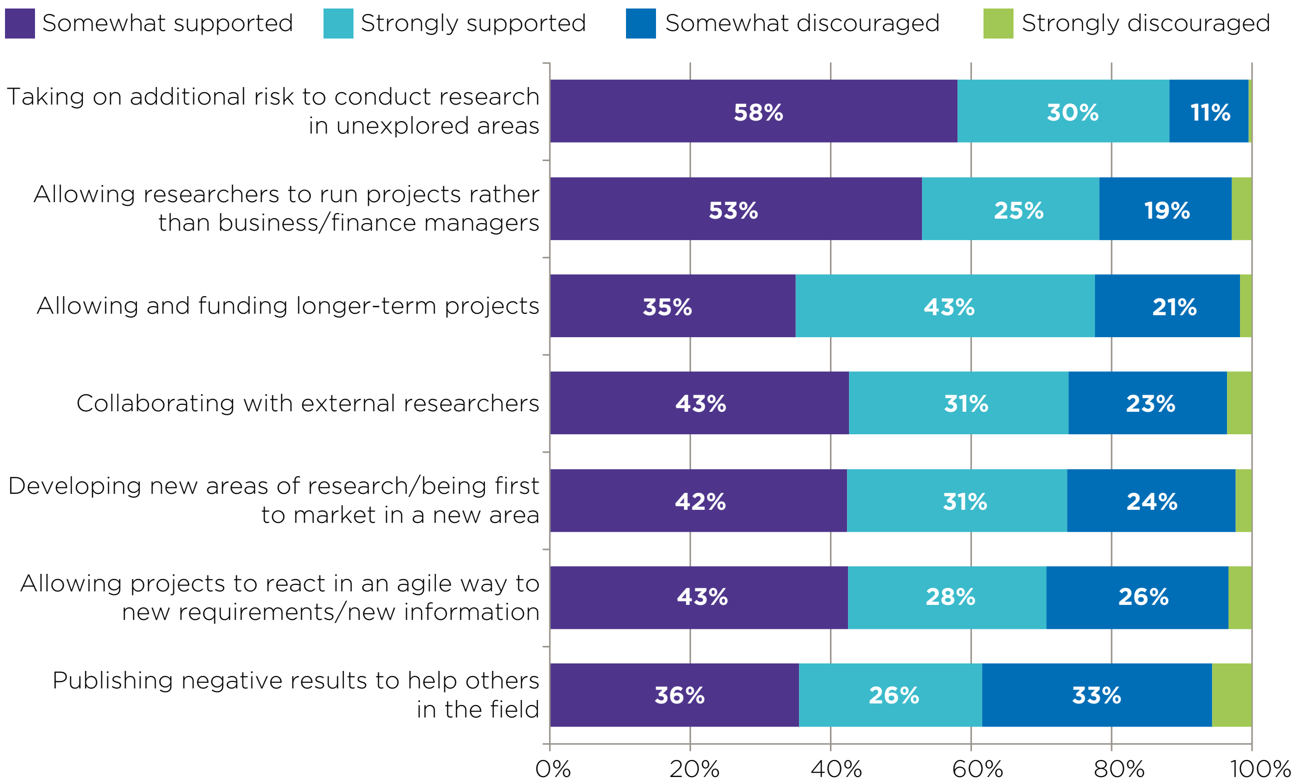
[61] McKinsey Global Institute, *Measuring The Economic Impact Of Short-Termism*, 2017
[62] Harvard Law School Forum on Corporate Governance, *Funding the Future: Investing in Long-Horizon Innovation*, 2020

> **"It seems that there is less and less willingness to do long-term research."**
>
> *Kai Peters, Research & Innovation Policy Advisor, VDMA*

A fear of risk among funders and institutions is another issue. One study[63] finds that the quality of internal innovation declines following an initial public offering (IPO), i.e., offering shares on the stock exchange, and firms experience both an exodus of skilled inventors and a decline in productivity among remaining inventors (although this is tempered by a change in strategy to acquiring external innovation).

Despite these studies, our respondents generally consider their funding environments supportive. More than four in ten (43%) described the length of most of the funding cycles in their department as 5–10 years, and over a third (37%) said that cycles had lengthened over the past 10 years. Large proportions of respondents also felt that senior managers at their organisation were supportive towards research productivity (see figure below). However it should be noted that a perception of leadership support for longer-term projects does not necessarily mean that those longer-term projects actually happen, for instance if managers' time in post is shorter than the projects they support.

Fig. 14: To what extent do senior managers at your organization OR at your funders' organizations support and facilitate the following?



Source: Oxford Economics

[63] Bernstein, *Does Going Public Affect Innovation?*, 2012

2.3.3 Focus on short term may be reducing "blue sky" research

Blue sky research is sometimes used synonymously with basic research, in that it is the study of new areas of science with no initial view as to the application of any findings. While this type of research can be short-term in nature and ultimately lead to very useful innovations, there are plenty of examples of much longer-term blue sky research projects, sometimes with very large capital investments, such as the Large Hadron Collider (LHC).[64]

A general shift in focus toward shorter funding cycles may however mean a greater concentration on the type of smaller evolutionary improvements possible with lower time and financial budgets, and a reduced focus on the type of longer-term research in new areas that could deliver revolutionary innovations. Our survey findings reflect this: **Three quarters (74%) agreed that shorter funding cycles lead to less research in unexplored areas.** Indeed, **59% of respondents in basic research felt that longer funding cycles are not available, limiting focus on broader research areas**, more than the 55% and 52% across applied research and experimental development.

Governments are an important contributor to the funding of some of these types of long-term blue sky research projects. For instance, the LHC is operated by the European Organisation for Nuclear Research (CERN), which is funded by member governments based on the size of their GDP. As discussed in section 2.4, government funding for R&D has been growing each year only marginally across many of our focus countries since the start of the century, and may even be marginally falling in real terms in some of these locations. As a result, this means that it has been falling as a share of total R&D spending from all sources. This could be a further cause for concern that less progress will be made in this type of research in the years ahead.

> **"In the corporate world, R&D spending has been going up but the shift has been out of long-term R&D and into short-term research."**
>
> *Director, not-for-profit research organisation*

[64] The world's largest particle accelerator, built underground across the France-Switzerland border with the purpose of allowing physicists to test particle physics theories.

2.4 COLLABORATION, OUTSOURCING AND PRODUCTIVITY

2.4.1 Academic collaboration is important to success

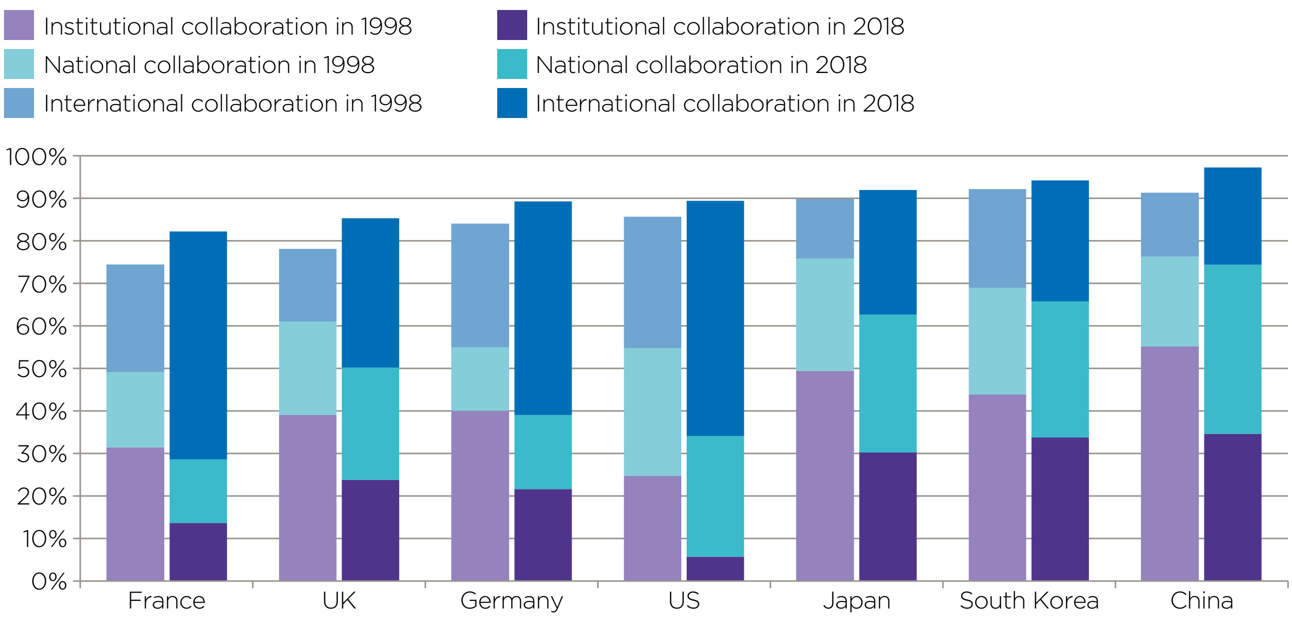
Approximately half (49%) of our survey respondents believed that a high level of internal collaboration is critical to supporting scientific research productivity, with more than a third (36%) saying the same for external collaboration.

These findings are confirmed by our **econometric modelling based on data from top US universities, which found that that academic collaboration (defined as the number of authors on a paper) is linked to higher levels of research productivity** (as measured by citation-weighted publication numbers per million dollars of R&D spending). This impact is greater when collaboration takes place between universities, including international collaboration, rather than among co-authors within an institution.[65]

These findings, combined with time series data on the prevalence of collaboration among academics, suggests that this trend has supported improved productivity in basic research over the past 20 years. The total share of academic output (such as published papers, books, conference papers) produced through a collaborative effort has risen in each of our focus countries. In addition, the share of international collaboration has notably expanded in many countries, while the percentage of collaborations within institutions has shrunk.

Existing literature also finds that collaboration between universities and industry can increase academic researchers' productivity,[66] particularly when research groups collaborate with industry over the long term.[67] Examples of universities collaborating with industry can be found in the aerospace and defence sectors for example, where a manufacturing firm might work with university researchers to develop a new piece of technology.

Fig. 15: Share of academic output produced through collaboration, by collaboration type, country and year



Source: Scival, Oxford Economics

[65] This may in part be expected: longer-distance collaborations may be more likely to involve the most impactful researchers in different countries and institutions, as their expertise is sought from afar.
[66] Landry, Traore and Godin, *An econometric analysis of the effect of collaboration on academic research productivity*, 1996
[67] Garcia, *How long-term university-industry collaboration shapes the academic productivity of research groups*, 2019

Other evidence suggests that greater collaboration within the business sector yields a positive impact on product innovation. For instance, one paper[68] finds that in Turkey between 2006 and 2008, firms engaged in external collaboration during the innovation process obtain better improvements in their products and markets, as well as improvements to their production processes.

Despite these benefits from collaboration, a third of our respondents believed that difficulty managing partnerships and outsourcing is a significant barrier to research productivity for their industry. We also heard through interviews with senior researchers that establishing and developing effective partnerships can demand substantial time, and can create sensitivities around the intellectual property generated by the partnership.

[68] Findik and Beyhan, *The Impact of External Collaborations on Firm Innovation Performance*, 2015

2.4.2 Diversity seen as important to research productivity

Much has been written about the potential benefits of diversity in workforces based on anecdotal evidence. Though difficult to measure quantitatively, benefits often ascribed to having more diverse teams (in terms of characteristics such as age, race, religion, gender) include reduced costs, better products and services and improved creativity and problem-solving.[69] **In our survey, 37% of respondents believed that having diversity in research teams was critical to supporting scientific research productivity.** This is encouraging, as approximately four in ten respondents believed that their research department was highly diverse in terms of age and gender identity, and three in ten for nationality, with approximately a further 50% saying their teams were somewhat diverse in these areas.

Another way of defining diversity would be in terms of the research disciplines of team members. Anecdotally we have heard that research teams can benefit by having people from a variety of scientific disciplines. However, one analysis[70] suggests that inter-disciplinary research terms face obstacles such as a loss of efficiency because team members have to learn new fields. In our survey, one in three reported that their teams were very diverse in terms of research discipline.

2.4.3 Bureaucracy and administration take their toll on research productivity

Over three quarters (80%) of respondents in our survey report that administrative duties reduce the time that they and their team have available for research, with a third saying the administrative burden completely or substantially affects their time. This reflects anecdotal evidence gathered during our interview process, as well as other studies. One investigation found that 44% of surveyed researchers (three quarters of whom were in the UK) agree that their organisation expects them to take on several roles, leaving little time for research.[71] Another reports that an average of 42% of the time spent on US federally-funded projects was spent on administrative duties associated with the project rather than research, spread across many tasks required by different funding agencies, auditing and accrediting agencies and academic institutions.[72] These studies and our consultations highlight how especially for academics there are frustrations that teaching and administrative duties are prioritised over research.

One administrative duty that may be causing a strain on researchers is the increasingly complex process of applying for research funds—**61% of our survey respondents reported that this increased application complexity is meaningfully detrimental to the productivity of scientific research**. This finding is broadly consistent across respondents from all stages of research and industries, suggesting it might apply to all sources of potential funding.

2.4.4 Outsourcing not a panacea for research productivity

In recent years, a strong trend towards outsourcing—i.e. paying a third party to carry out agreed R&D tasks—is evident in some fields of research.[73] This marks a reversal of the trend seen in the "golden age of the corporate R&D lab" during the first half of the twentieth century, when the share of industrial research spending contracted to outside the firm fell to just 3%.[74] Since then, the share grew to approximately 12% by 2015,[75] and market analysis suggests current annual growth of 10%–12% in demand for the services of pharmaceutical contract research organisations in particular.[76]

[69] Findik and Beyhan, *The Impact of External Collaborations on Firm Innovation Performance*, 2015
[70] LSE blogs, Erin Leahey, Interdisciplinary research may lead to increased visibility but also depresses scholarly productivity, 2017
[71] Wellcome, *What Researchers Think About the Culture They Work In*, 2020
[72] US National Institutes of Health, *The FDP Faculty Burden Survey*, 2009
[73] Some outsourcing relationships can be highly collaborative, but are distinct from the collaboration discussed above due to the financial model of one party contracting and paying the other
[74] EARTO, *Research and Technology Organisations In The Evolving European Research Area*
[75] Knott, *R&D Outsourcing and the Decline in R&D Productivity*, 2020
[76] Clearwater International Healthcare, *Outsourced Pharma Services*, 2019

There are certainly advantages to outsourcing for scientists. In particular, biotech and pharmaceutical firms were some of the first to embrace this trend, using contract research organisations to run drug trials to reduce the time needed for a new product to reach market.[77] And for other research disciplines, outsourcing to a contract technology provider helps researchers to avoid the high investment cost of purchasing new equipment that may rapidly become superseded.[78] If managed well, outsourcing may well help reduce R&D costs.[79]

However, this trend also brings aspects that are less conducive to research productivity. Suggested reasons range from inferior resources at external organisations, potentially leading to expensive but unusable results, or more involvement being required than originally thought, reducing cost savings.[80] A potentially more problematic longer-term inefficiency associated with outsourcing is the transfer of knowledge to the contracting partner, meaning the researching scientist loses technical knowledge. This can make it more difficult to address problems, or to extend the research to new applications. Concerns have also been raised that reliance on external partners, rather than conducting all research in-house, may limit freedom to operate, and hence limit the creativity needed for innovative new research.[81]

These concerns are highlighted by the findings of empirical studies. For instance, one report found that a sustained decline in R&D productivity appears to come from a substantial reallocation of research activity from in-house to external organisations.[82] We have also conducted our econometric modelling and find that **outsourcing is associated with lower research productivity among firms in the US and UK, in both the short term and the long term.**[83]

Overall, outsourcing may reduce costs but at the same time have long-term negative consequences for research productivity. Results from our survey reflect this: while **two thirds (64%) said outsourcing research allows their team to deliver results more quickly, and 75% said outsourcing has improved their department's return on research investment, nearly half (45%) said outsourcing means the organisation loses knowledge that would improve in-house research efficiency. Furthermore, 37% believe outsourcing leads to a decline in research productivity over the long term and 55% noted a significant administrative overhead in managing an outsourcing relationship.**

2.5 GOVERNMENTS GENERALLY SUPPORTIVE OF R&D BUT COULD FUND MORE

2.5.1 Government seen as prioritising R&D in its industrial strategy

Respondents in our survey believe their governments are generally supportive of R&D—**more than three quarters (77%) said their country's government adequately prioritised scientific R&D as part of its industrial strategy, and 69% believed the level of government support and leadership was not a substantial barrier to research productivity.**

The elements of government involvement that respondents found especially supportive included: strategy around particular focus areas; supporting technology transfer; and supporting state-run R&D facilities and business incubators—with approximately three in ten reporting "strong support" in these areas.

[77] Mortimer, *Time is ripe*, Nature, 2007
[78] Pichler and Turner, *The power and pitfalls of outsourcing*, Nature, 2007
[79] PwC, *R&D outsourcing in hi-tech industries,* 2013
[80] Pichler and Turner, *The power and pitfalls of outsourcing*, Nature, 2007
[81] Smith, *The outsourcing and commercialization of science,* 2015
[82] Knott, *R&D Outsourcing and the Decline in R&D Productivity*, 2020
[83] For more details, see Appendix 2.

SPOTLIGHT ON LARGER FIRMS

Perhaps unsurprisingly, respondents from larger firms tend to face more complexity and collaboration challenges than their peers at smaller organizations.

For example, respondents from firms with more than $1 billion in annual revenue are more likely to say carrying out scientific research in their field is increasingly complex—30%, vs. 25% of firms with under $1 billion. Administrative burdens pose a threat to productivity, too, and firms with the largest R&D budgets (over $100m) are more likely to say administrative burdens have a substantial impact on time available for research.

The largest firms in the sample—companies with more than $50 billion in reported revenue—are more likely than smaller organizations to say they have larger research teams, yet are less likely to report a high level of internal collaboration at their organization. Outsourcing could be a symptom or a cause of these collaboration challenges: larger organizations are more likely to say that outsourcing has improved return on research investment (89% among those with $50 billion or more, vs. 73% of smaller organizations).

Larger organizations are more strongly positioned than others in some key areas. Perhaps due to their broader financial and talent resources, companies with $50 billion or more in revenue are less likely to say many technology investments have helped less than anticipated.

2.5.2 Public funding in the right areas is one topic where researchers call for more support

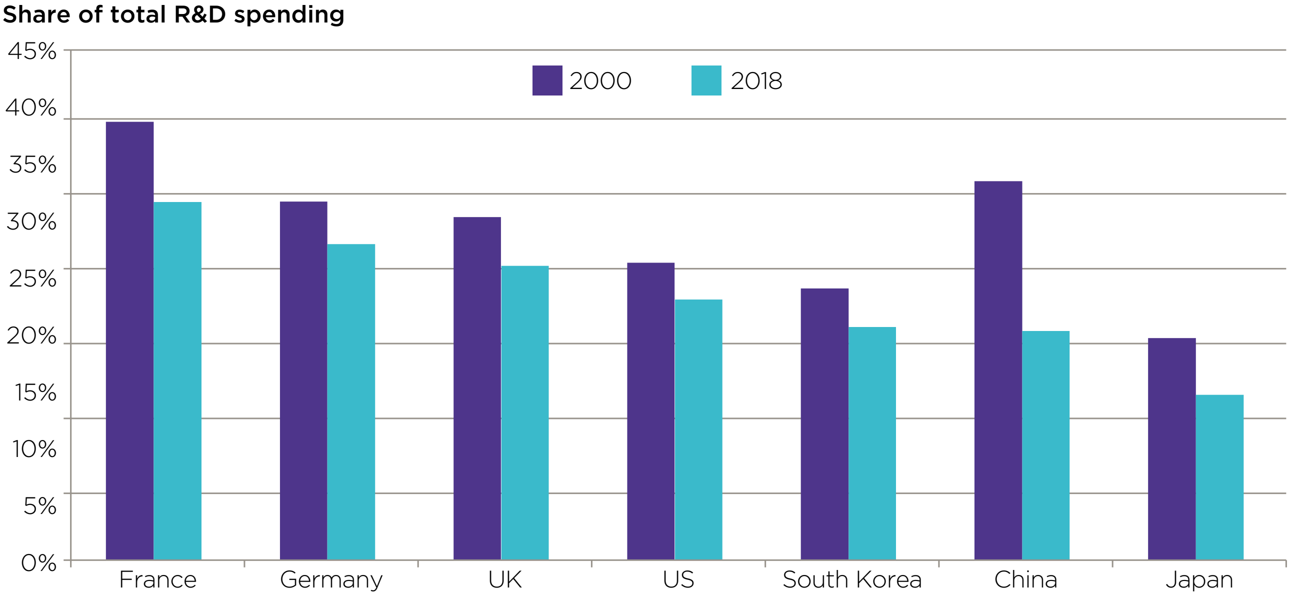
Although **the majority (63%) of survey respondents reported that their government provides "enough" support in terms of adequate funding for R&D, just 15% reported "strong support" in this area and 22% believed there is not enough support.**

Trends in government funding for R&D in recent years vary significantly across our focus countries. For instance, public research spending rapidly increased by an average of 15.5% in China between 2003 and 2018 in nominal terms, as part of a government effort to boost "indigenous innovation."[84] Although this growth came from a relatively small base, this rapid pace of expansion has been sustained, growing by 14% in 2018 alone. Likewise, South Korea's expenditures rapidly increased from a small base early in the millennium, although this pace has slowed more recently. A very different trend is evident in the remainder of our focus countries, with very low average annual growth rates in nominal terms, alongside growth in GDP that is similarly sluggish by comparison.

One trend visible across each of the countries we focused on is that growth in government funding for R&D is far outpaced by growth in research spending by the business sector. This is shown in figure 16, where the government's share of total R&D funding has fallen in each country since 2000, and particularly notably so in China as business spending has picked up.

[84] All findings in this paragraph based on analysis conducted on figures from Eurostat's R&D database.

Fig. 16: Government R&D funding as a share of total R&D funding



Source: Eurostat, Oxford Economics calculations

Approximately three in ten in our survey felt that direct government funding was inadequate, compared to fewer than one in ten regarding private sector funding. Similarly, approximately one in four felt that the availability of direct government funding for R&D had worsened over the past 10 years, compared to one in ten for private sector funding.

Adequate government funding is important for a number of reasons. First, it provides essential support for basic research, the foundation of new innovation. Second, it can be a lever for attracting additional private-sector investment. One UK study finds that £1 of public R&D generates between £1.21 and £3.16 of private sector investment depending on the country after approximately ten years.[85]

Equally critical is the issue of how well funds are targeted. **Just one quarter of our respondents felt that the balance of funding and focus on the different stages of research is about right.** Nearly three in ten (29%) respondents felt that direct government funding for experimental development is inadequate in their country—more than the 26% said the same for basic research and 23% for applied research.

In the US and Europe, government spending on experimental development has perhaps not been as high a priority as supporting basic or applied research. For instance in 2018, just a quarter of UK government R&D spending was on experimental development, and half of that was specifically on defence projects.[86] A similar story has been true across the EU on average—in 2013 for instance, 52% of EU government R&D budgets went to basic research, including 57% in Germany,[87] leaving less than half for both applied research and experimental development. In the US, while federal government funding is relatively evenly split across the three stages of research, basic research comprised 42% of all R&D spending in 2018 and 34% of all applied research spending, while just 13% was devoted to experimental development.[88]

[85] UK BEIS, *The relationship between public and private R&D funding*, 2020
[86] UK Office for National Statistics, *Research and development expenditure by the UK government: 2018*, 2020
[87] UNESCO, *What is the optimal balance between basic and applied research?*, 2017
[88] Congressional Research Service, *US Research and Development Funding & Performance Fact Sheet*, 2020

The way resources are allocated is significant as it relates to the impact of R&D on real life outcomes, such as economic growth, quality of life or life expectancy. As a novel innovation moves up the scale of technology readiness, costs rise exponentially in the effort to get closer to market.[89] [90] This means that every dollar of government funding at the basic or applied research stages will demand a significantly larger amount of funding at the experimental development stage to translate the innovation from a concept into something real. But funding of this magnitude is often not available from the government in many countries. Put another way, there is no linear correlation between public sector funding at the basic research stage and real-market outcomes.

It can be argued that businesses are the ones that benefit most from developing new products and selling them on the market, and as such, should be the ones to pay for this development. However, "there is a need to expand mission-driven R&D for tackling industrial and societal needs" [91] that cannot be fulfilled by funding laboratory work. Some research-industry bodies[92] [93] are therefore calling for an increased focus on the experimental development stage to help address this need. Suggestions for, and examples of, government help in this area include setting up consortia to address research in a particular focus area, running innovation competitions in particular research areas, and allowing companies to access public infrastructure for R&D purposes.

An increase in funding for experimental development should not be at the expense of funds allocated to long-term basic research in new areas with no specific end product or technology in mind, however, given this is the foundation for new innovation.

SPOTLIGHT ON PRIVATE-SECTOR FIRMS

Three quarters (73%) of our respondents agreed that the pressure to produce results or publish papers had increased over the past 10 years, with 28% strongly agreeing with this notion. As might be expected it was also a much greater issue for those in private, for-profit businesses (75%) than in not-for-profit organisations (62%).

In addition, 59% felt that pressure from management to produce results as soon as possible was detrimental to scientific research productivity, particularly in private, for-profit companies where 63% found this to be true.

[89] EIT Health, *Technology Readiness Levels: NASA's contribution to Horizon 2020*

[90] Mihály Héder, *From NASA to EU: the evolution of the TRL scale in Public Sector Innovation*, 2017

[91] European Association of Research & Technology Organisations / Technopolis Group, *Getting the Balance Right: Basic Research, Missions and Governance for Horizon 2020*, 2012

[92] Ibid.

[93] UK Association of Innovation, Research and Technology Organisations, *More D! A more development-focused strategy for paving the way to impact,* 2020

3. CONCLUSION

We find it is impossible to make one conclusive statement about the trajectory of scientific research productivity, but our global study shows that science faces significant headwinds in important areas of discovery and development. Researchers around the world and across different stages of work are confronted by several common obstacles and circumstances that must be improved to enable efficiencies and maintain the long arc of progress. Leaving these challenges unaddressed could incur unacceptably high costs in both economic and human terms.

There is at the same time much room for optimism. Our program identified several bright spots across countries, industries, and stages of research. And of course the most newsworthy scientific research accomplishment of the young decade is the rapid development of vaccines in response to COVID-19. This is a story that brings together many of the factors we have encountered in our study, including huge amounts of collaboration across disciplines and national borders; demand led by central governments; and the novel deployment of research that had been carried out with a different use case in mind.

The true magnitude of this research triumph may not be known for years. Already there is hope that mRNA advances used in some COVID-19 vaccines will prove effective in treating or preventing other illnesses, including some cancers. This example—like many throughout history, hastened by the necessity of extreme circumstance—provides strong evidence that scientific research need not muddle ahead on a plateau, but can create great and necessary things if the right conditions are in place.

And there is no doubt that this century so far has seen remarkable progress in many other areas: medical researchers devised new cancer treatment, personalised for each patient, known as CAR T-cell therapy;[94] astronomers produced the first ever photo of a black hole,[95] and since the introduction of the first "3G" mobile phone network in Japan in 2001 and the unveiling of the first iPhone in 2007, the rise of the smartphone has helped to connect people around the world.[96]

As the frontier of scientific knowledge is advanced, we find that **greater complexity can lead to lower productivity.** This may be in part due to the fact that much of the "low-hanging fruit" in the sense of developments possible from a single researcher has already been picked, and research today requires larger teams with a greater breadth of individual expertise. These larger efforts come with administrative overheads, particularly when spread over several sites or countries—this is a productivity trade-off that must be considered against the benefits of being able to perform more advanced research.

One trouble-spot that appeared consistently throughout our investigation involved the related themes of **short-termism and pressure to produce results**. These were often identified as budget-related problems that affect both the quality and the scope of research—being tied to shorter time-horizons limits the size of the questions that can be investigated, and greater pressure to get things done as quickly as possible leads to errors and adverse incentives. Of particular note is the fact that projects with long timeframes and limited requirements to produce results are essential to create new knowledge in some areas of science, including applications not dreamed of at the start; the basic research that underlies all other advances is thus imperilled.

Collaboration is another critical theme. The benefits of working together were seen through many of our avenues of analysis and were identified as something that should be encouraged, to avoid the inefficiencies associated with working in silos. However,

94 US National Cancer Institute, *Milestones in Cancer Research and Discovery*
95 Nature, *Black hole pictured for first time — in spectacular detail*, 2019
96 Science Node, *A brief history of the smartphone*, 2018

there are risks with this approach: we also found that as complexity of research rises with each technology's level of development maturity, larger teams with a greater number of specializations are required. Larger teams provide additional expertise and capability, allowing more innovative new science to be done. However, as noted above, it is a trade-off, as larger teams, particularly when spread over multiple sites, are associated with lower marginal productivity, so it is clear that working relationships must be closely managed to gain the benefits and avoid the risks.

A further risk factor for productivity is **outsourcing**. Outsourcing has generally been a feature of corporate life in recent decades, as operations are offshored or contracted to third-party service providers, and it has been happening within scientific research since the golden age of the corporate laboratories began to wane in the 1960s. The goal is efficiency, but this can be a two-edged sword. While certain benefits can accrue, such as enabling projects to run faster, our research finds that overall outsourcing leads to weaker research productivity, potentially through a loss of internal knowledge and skills. Again, this is an area that must be carefully managed for benefits to be realised without unexpected costs to the long-term growth of any business.

Lastly, we found that **government support for R&D** is an important factor to consider. In our interviews with researchers around the world we found that having a government that prioritises R&D is important, and our survey identified that respondents are happy with the overall current general level of support in their country. However, the amount of public funding for research was one area that interviewees and survey respondents generally felt could be improved, reflecting slow rates of growth in funding in recent years in western economies.

The productivity of scientific research is a difficult thing to measure, and is an important field of study in its own right. The appropriateness of different metrics may change over time and according to the specific research outputs in focus. But there is agreement, both broadly and among our survey respondents, that some widely-used metrics, such as number of publications per researcher or research dollar, can incentivise behaviours that are detrimental to research quality and to the corporate culture of research institutions.

Our broad inquiry revealed many aspects of scientific endeavour that require attention and concerted effort if research productivity is to sustain the pace necessary to meet the critical needs of society and business. Our study was focused on examining the state of scientific research productivity, rather than exploring specific policy or other recommendations. Nevertheless, we asked the experts we consulted for their views on measures that could best support long-term growth in scientific research productivity. We put these forward in the next chapter in order to stimulate debate and attention to the important question of how to sustain productivity in what is ultimately the most important foundation for human progress and well-being.


SENSOPART

4. RECOMMENDATIONS: THE EXPERTS SPEAK

Our investigation into the state of scientific research productivity—including interviews and workshops with scientists and researchers, a bespoke survey of experts, and a broad review of literature on the subject—revealed a number of ways in which policymakers, industry associations, and organisations can support R&D in the future. These suggestions were not unanimously agreed on by the experts consulted, or endorsed by the report's authors, but are presented with the intention of stimulating further discussion and collaboration.

4.1 MAKE FUNDING MORE SCIENTIFIC: INCREASING THE RIGOR OF PUBLIC RESEARCH FUNDING

Researchers are well-versed in the scientific method of designing experiments to gather data and test hypotheses, yet this approach is not always used to determine the best way to allocate finances.

Some of our interviewees believed that greater application of the scientific method to determining research funding would help ensure that public money is put to its best use—a belief supported by existing literature.[97] Factors that could be tested this way include the size, age, or diversity of research teams; use of interdisciplinary collaboration; and how best to commercialise innovations. However other interviewees felt this would be too restrictive and that project leaders should decide team composition.

Respondents also noted that a greater reliance on literature reviews when deciding grant allocations would help reduce the risk of financing duplicative work, avoiding research already carried out and reported by others.

Alternative methods of funding could also be considered to increase the diversity of projects being funded. These could include lotteries, where projects need to meet a minimum scientific robustness threshold but otherwise are decided based on chance.[98] This would have the advantage of reducing administrative time spent on writing grant proposals. Other funding methods could be pushed into the mainstream, such as funding researchers rather than projects. This approach is taken at the Howard Hughes Medical Institute for instance, and a study[99] finds that researchers there produce high-impact papers at a higher rate than a control group of other similarly-accomplished researchers elsewhere. However, it should be noted that this approach may disadvantage early-career researchers that are not able to gain this type of funding.

[97] Nature, *Research efficiency: Turn the scientific method on ourselves*, 2012
[98] NESTA, *A random approach to innovation*, 2018
[99] Azoulay et al, *Incentives and creativity: evidence from the academic life sciences*, 2009

4.2 TAKE THE LONG VIEW: FOCUSING ON APPLICATIONS OF RESEARCH OUTPUTS

Continued investment in blue-sky research—work that advances human knowledge without obvious applications or commercial benefits—is essential. But in research slightly higher up the technology readiness levels, it is also important to not lose sight of possible uses.

Government-funded researchers should bear in mind how their foundational work will benefit society. In the UK, scientists using government funds are asked to demonstrate how what they are doing could have useful applications. Maintaining the purity of basic research is essential, but our interviewees believe an outcomes-based view is necessary to boosting scientific research productivity.

Adequate support from government should also be provided for smaller companies and universities to translate promising ideas into products.

4.3 GET THE WORD OUT: PROMOTING WIDER DISSEMINATION OF RESULTS

One important aspect of research on the COVID-19 virus was a sharp rise in sharing research findings through "pre-prints" (articles posted online before peer review").[100] Indeed, momentum was growing to share results early and to open access to work even before the pandemic.[101] However, pre-prints do not follow the traditional peer-review method, and as such the level of quality cannot be guaranteed.

Dissemination of research results is still largely done through journals that are read chiefly by academics, leaving some organisations that could benefit from the research less informed. Making research findings more accessible is important, as our literature review indicates;[102] many scientific findings remain unexploited by society because knowledge is not always published by private sector researchers, and open management of knowledge is not being promoted or rewarded in scientific practice.

Opening the culture of science and innovation can generate greater benefits. One example of an initiative to promote this is "cOAlition S" (where the capitalised OA represents open access and the S represents science).[103] This is an international consortium of research funding and performing organisations calling for research funded by public grants to be published in open access journals or platforms.

[100] Nature, *How a torrent of COVID science changed research publishing,* 2020
[101] Nature, *Will the pandemic permanently alter scientific publishing?*, 2020
[102] High-Tech Forum, *Open Science and Innovation,* 2020
[103] cOAlition S, *What is cOAlition S?*

4.4 LOOK BEYOND THE NEXT FUNDING CYCLE: AVOIDING SHORT-TERMISM

Our survey and interviews revealed the extent to which experts believe short-termism in terms of funding and research cycles is detrimental to research productivity, and in particular to pioneering discoveries in new areas of science.

Lengthening the investment timescales for projects involving public funding—both for individual projects and overall funding programmes—is seen as essential. The UK's new Advanced Research and Invention Agency,[104] which will focus on providing financing for high-risk, high-reward applied scientific research, was cited as an example of government initiatives that may help to counter the trend towards short-term thinking. However, funding for agencies such as this should not come at the expense of blue sky basic research. More generally, the standard length of grants awarded from public funding could be increased.

Beyond funding, our interviewees also recommended against relying on short-term returns on projects, allowing entrepreneurs (particularly in universities) to increase the horizon for monetary returns, and to allow research groups to explore the route to technology transfer/translation more organically, rather than prescribing the need for a fixed plan at the start of a project.

4.5 APPLY BETTER METRICS: IMPROVING MEASURES OF PRODUCTIVITY

Measuring and tracking scientific productivity is difficult, particularly at a broad scale. But current methods of measurement and optimisation can be improved, helping to give taxpayers confidence that their taxes are being used effectively. Fields of research such as "bibliometrics" exist to try to determine the best ways of measuring certain types of academic research productivity. The new and broader field of "research on research" is a growing one, as seen for instance by the opening of the Research on Research Institute[105] in London in 2019.

Our interviewees recommended that additional studies should be conducted on research productivity, as better understanding could help lead to better outcomes. Relatively small increases in productivity could have a significant impact, given the large amounts of money and resources involved.

4.6 WORK TOGETHER: ENCOURAGING AND SUPPORTING COLLABORATION

Collaboration helps drive productivity in scientific research. Our interviewees suggested a number of ways to support collaboration, including:

- Ensure goals are clear and aligned between all those involved, and have metrics in place to measure progress towards those goals.
- Enable transparent communication, with common languages in use so teams from different disciplines understand one another.
- Enable the movement of individuals between academia and industry, such as through the Royal Society Industrial Fellowships seen in the UK.

Similar recommendations can be found in literature from industry associations, such as promoting collaboration rather than competition when it comes to accessing public funds[106] and promoting collaboration on scientific research between countries in the EU.[107]

[104] Gov.UK, UK to launch new research agency to support high risk, high reward science, 2021
[105] Research On Research Institute
[106] AIRTO, *More D!*, 2020
[107] EARTO, *Joint contribution to the public consultation on Interregional Innovation Investments*, 2020

4.7 PLAN FOR THE BIG PICTURE: PROVIDING GREATER PUBLIC GUIDANCE AND SUPPORT IN KEY STRATEGIC AREAS

The COVID-19 crisis provided an excellent case study of what is possible when there is a clear call to action, backed by significant demand from customers in the form of national governments. Similar themes of rapid technological innovation have been seen during wartime, including the Cold War, which drove the space race.

Our interviewees recommend that governments make similar investments in areas that are strategic to national well-being and security. This would enable systems to be in place and fundamental research already carried out to help deal rapidly with emergency situations. Mitigating climate change may be an obvious example. However, this should not be done at the expense of existing funding for other areas.

A similar approach could be used to help improve national well-being in important but non-emergency situations, for instance improving the technological infrastructure of a country. Our interviewees noted that by acting as a single customer in these instances, the government can provide the scale of demand necessary to drive progress in these areas, and that acting as a direct customer rather than acting indirectly in the form of research grants may help to boost research productivity.

However, a number of interviewees voiced concern that, given finite government funding for scientific research, a research focus specified by government should not be implemented at the expense of existing funding for blue sky research with no concrete application in mind.

4.8 FOCUS ON TALENT: DEVELOPING A SKILLED WORKFORCE

Probably the most important element for any research effort is its human capital. Training and developing a skilled workforce, as well as attracting talent from elsewhere, is critical to the industry.

Industry associations and scientific organisations have developed recommendations on bolstering their workforce, such as ensuring sustained and predictable investments in graduate education and basic research budgets;[108] changing immigration rules so that it's easier to keep science graduates after their education courses end,[109] and making immigration easier for those with the required skills.[110]

[108] US National Science Foundation, *Our nation's future competitiveness relies on building a stem-capable US workforce*, 2018
[109] US Semiconductor Industry Association, *Winning The Future: A Blueprint for Sustained U.S. Leadership in Semiconductor Technology*, 2020
[110] German High-Tech Forum, *Ways to reach the 3.5% target*, 2019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5. THE SCIENTIFIC RESEARCH PRODUCTIVITY PULSE CHECK

The concept of scientific research productivity is a broad one, and the factors that support or hinder it are many and varied. All things considered, it is challenging to maintain an overarching view of the scientific productivity conditions prevailing in any given country or industry.

Indices such as the World Intellectual Property Office's Global Innovation Index,[111] the European Commission's Innovation Scoreboard,[112] and elements of the World Economic Forum's Global Competitiveness Index[113] cover the broad topic of scientific and business innovation but do not focus specifically on scientific research. We add to this body of work a new and unique framework that shows at a glance the views of the 3,500 scientists in our survey on the state of the enabling environment for scientific research in their organisation, country and industry sector.

5.1 A CONSTRUCT FOR UNDERSTANDING THE EXISTING STATE OF THE FACTORS SUPPORTING SCIENTIFIC PRODUCTIVITY

This report has sought to identify through various techniques the important factors that help or hinder scientific productivity. Our Scientific Research Productivity Pulse Check (referred to in this document simply as the "Pulse Check") focuses on the six quantifiable factors identified as most important within the four key driver themes that surfaced through our consultations, workshops and econometric modelling—more specific detail on which research channel led us to include each factor is given in Appendix 4.

The factors that we include in the Pulse Check are:

- **Freedom from short-termism:** we identified short-termism as a factor that limits scientific research productivity, so longer-term attitudes score higher in the Pulse Check;
- **Risk tolerance:** a risk-averse approach to research was identified as holding back research productivity, so a lesser degree of this thinking scores higher in the Pulse Check;
- **Strength of government support for R&D:** The consideration given to R&D in overall industrial strategy, as well as more specific measures such as state-run facilities and education programmes, was considered beneficial to productivity;
- **Freedom from administrative burden:** a lower burden imposed by administrative duties on the time available for research provides a higher Pulse Check score;
- **Collaboration:** collaboration on research projects is linked with greater research productivity and so a greater degree of collaboration gains a higher score. Conversely, we identified outsourcing as a factor related to collaboration that weighs on productivity, and so more outsourcing means a lower score;
- **Availability of funding:** greater funding availability gains a higher Pulse Check score. This factor is calculated based on survey responses as well as published data on total country R&D spending as a share of GDP.

We track each of these at the global level, to assess how far the world scientific community is from the best case, and then look deeper at each country and industry. The method that we use for this estimation is given in the box below.

[111] World Intellectual Property Organization, *Global Innovation Index 2020*
[112] European Commission, *European Innovation Scoreboard 2020*
[113] World Economic Forum, *Global Competitiveness Report 2020*

ASSESSING PERFORMANCE AGAINST THE FACTORS TRACKED IN THE SCIENTIFIC RESEARCH PRODUCTIVITY PULSE CHECK

We collected data on the different productivity enablers from our survey of 3,500 researchers around the world. This allows us to calculate a global average for each indicator, as well as an average for each country and industry.

We place these average responses on a scale from 0-100, where 0 is the theoretical worst case and 100 is the theoretical best case. For instance, within the "freedom from administrative burden" factor, a score of 100 would be every respondent stating that administrative duties do not detract at all from the time they have available for research, while a score of 0 would be every respondent reporting that administrative burden completely detracts from their research time.[114]

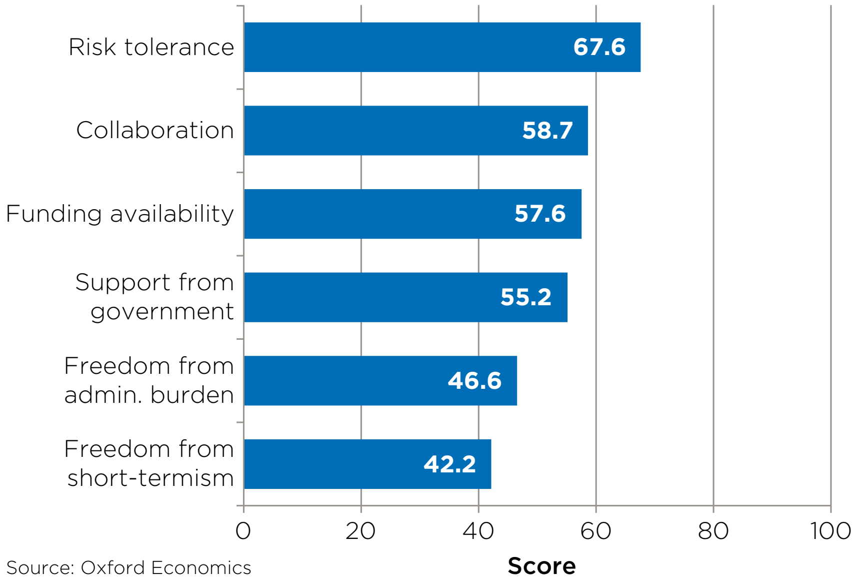
That is, the further a score is away from 100, the less supportive that factor is for scientific productivity. Further information on how the Pulse Check is constructed is provided in Appendix 4.

5.2 MAPPING THE GLOBAL STATUS OF PRODUCTIVITY ENABLERS

To begin with, we present the results for the status of the different factors across our focus countries as a whole, in figure 17.

These results show that short-termism is the issue where the current state of scientific research is furthest away from its best case, i.e. is the factor weighing most heavily on research productivity in the view of our survey respondents. The prevalence of risk aversion is closest to best case. Despite this, a score of 68 for risk tolerance still shows potential for improvement.

Fig. 17: Global results for each productivity factor



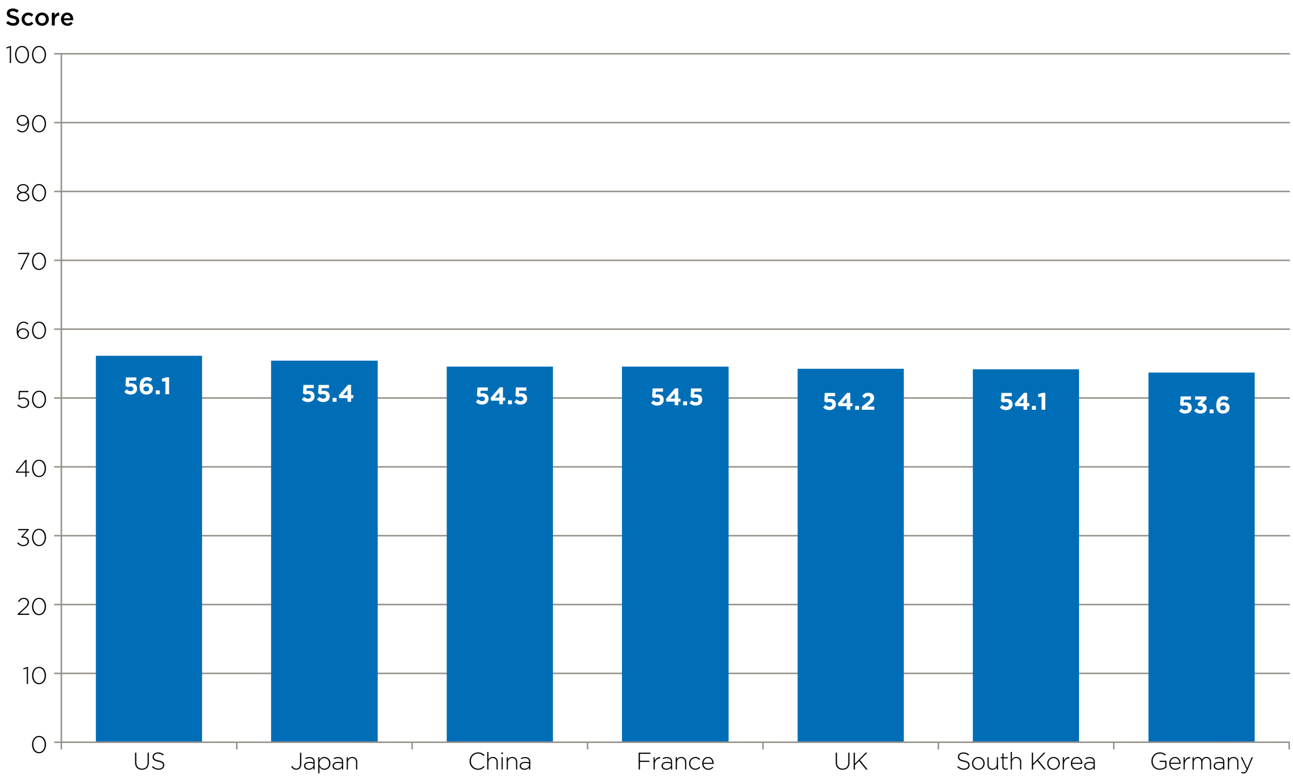
Source: Oxford Economics

[114] This could be half of respondents giving the worst-case answer and half giving the best-case answer, or all respondents giving the most moderate answer, or any equivalent mixture of responses.

5.3 MAPPING THE STATUS OF PRODUCTIVITY ENABLERS ACROSS COUNTRIES

Across the different productivity enablers highlighted above, we can also show the overall average score for each country, as illustrated in the chart below. The key point to note here is that the scores for each country are surprisingly close.[115] Below, we provide some commentary against each country to help describe what is driving each result.

Fig. 18: Overall Pulse Check results split by country



Source: Oxford Economics

[115] For a country to report a significant difference from another country across all six factors, an overall score differential of at least 2.5 points would be seen, equal only to the difference between the highest and lowest country scores. For more information on the Pulse Check, see Appendix 4.

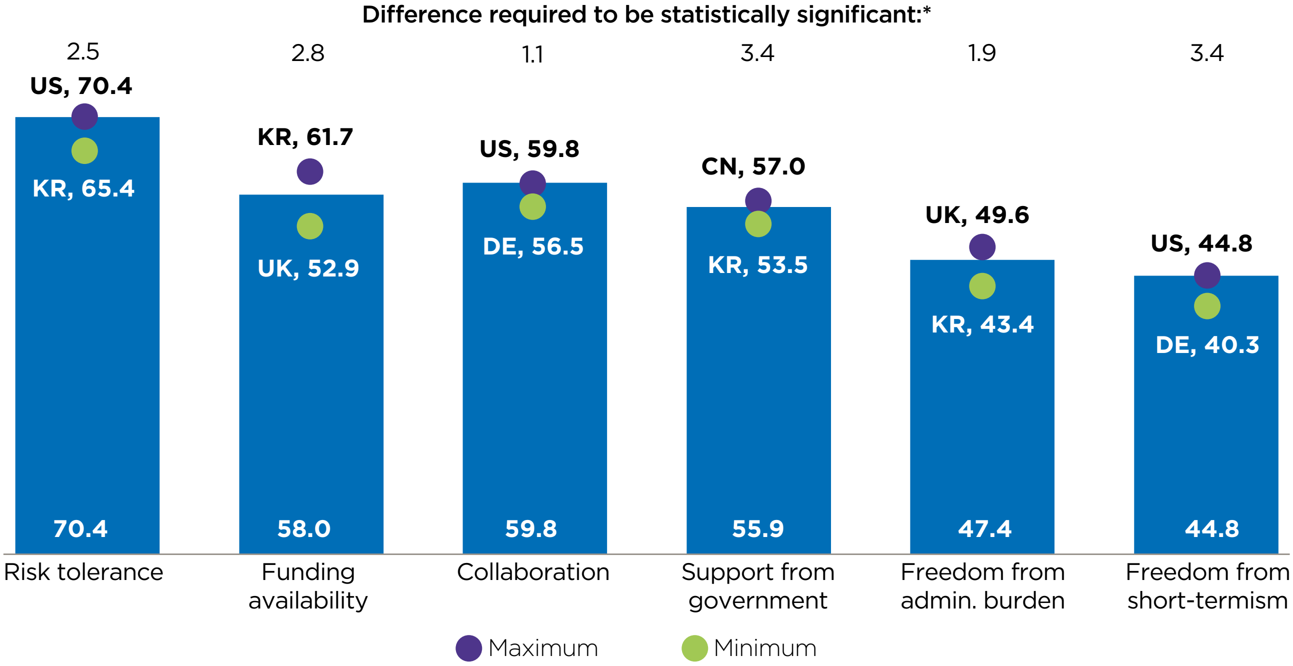
5.3.1 Breakdown of scores by country: United States

The US has many conditions supportive to research. For instance, data from our survey suggests that US organisations have the highest levels of research confidence, especially related to being the first to market in new areas of research and in publishing negative results to help others in the field, and to a lesser extent allowing projects to react in an agile way to new developments. These factors mean the US is furthest ahead, of our focus countries, in risk tolerance.

According to our survey, US organisations were also some of the most likely to collaborate with other institutions and businesses, and kept more of their research operations in-house, rather than outsourcing them.

Respondents also suggested favourable conditions in terms of long-term thinking, with less pressure on researchers from management to produce results as soon as possible.

Fig. 19: Pulse Check scores by factor for the United States against the minimum and maximum across all countries



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

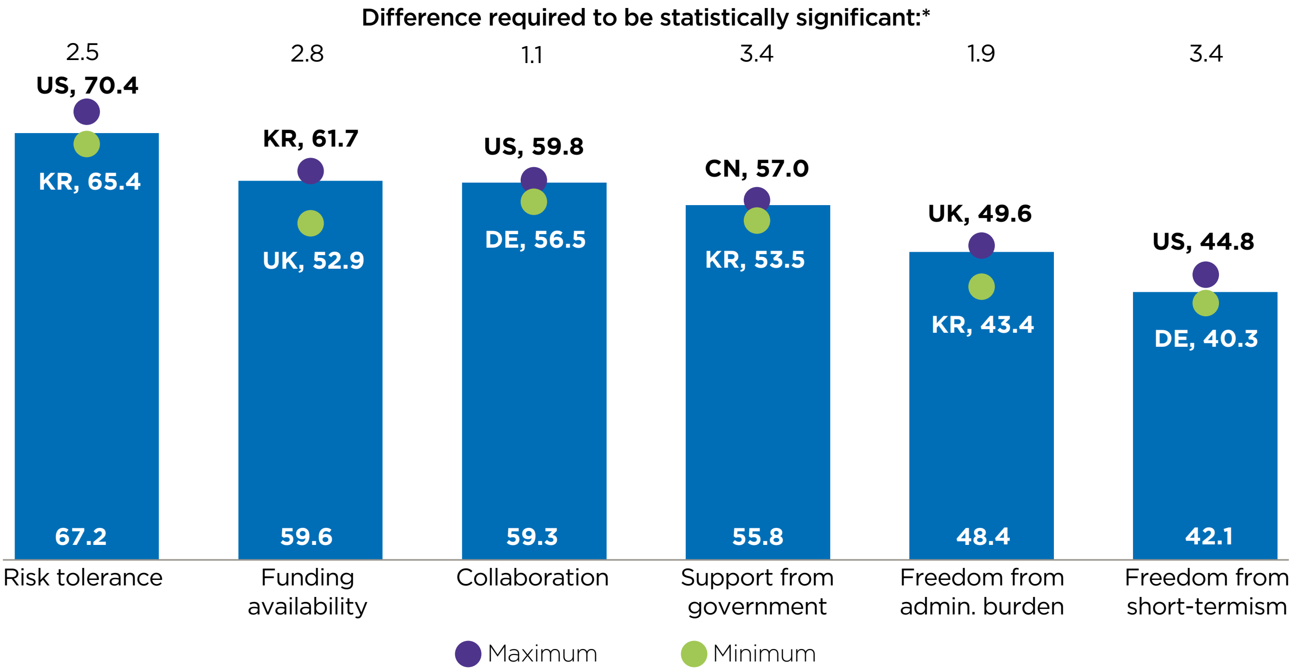
5.3.2 Breakdown of scores by country: Japan

Japan scored highly across several aspects of the Pulse Check, boosting the country's overall score. One aspect is the area of support from government for research, particularly the extent to which R&D is seen as being prioritised as part of industrial strategy and provision of state-run research facilities or start-up incubators.

Japanese researchers also enjoy relatively high levels of freedom from administrative burdens. Another factor supporting the country's overall score was the availability of funding reported by respondents. In particular, Japan spent the second-highest amount on R&D as a share of GDP out of our focus countries.[116]

However, one factor reducing the supportiveness of the research environment was the low degree of long-term thinking reported: survey respondents in Japan were among the most likely to rate research cycles as "very short term" (less than two years).

Fig. 20: Pulse Check scores by factor for Japan against the minimum and maximum across all countries



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

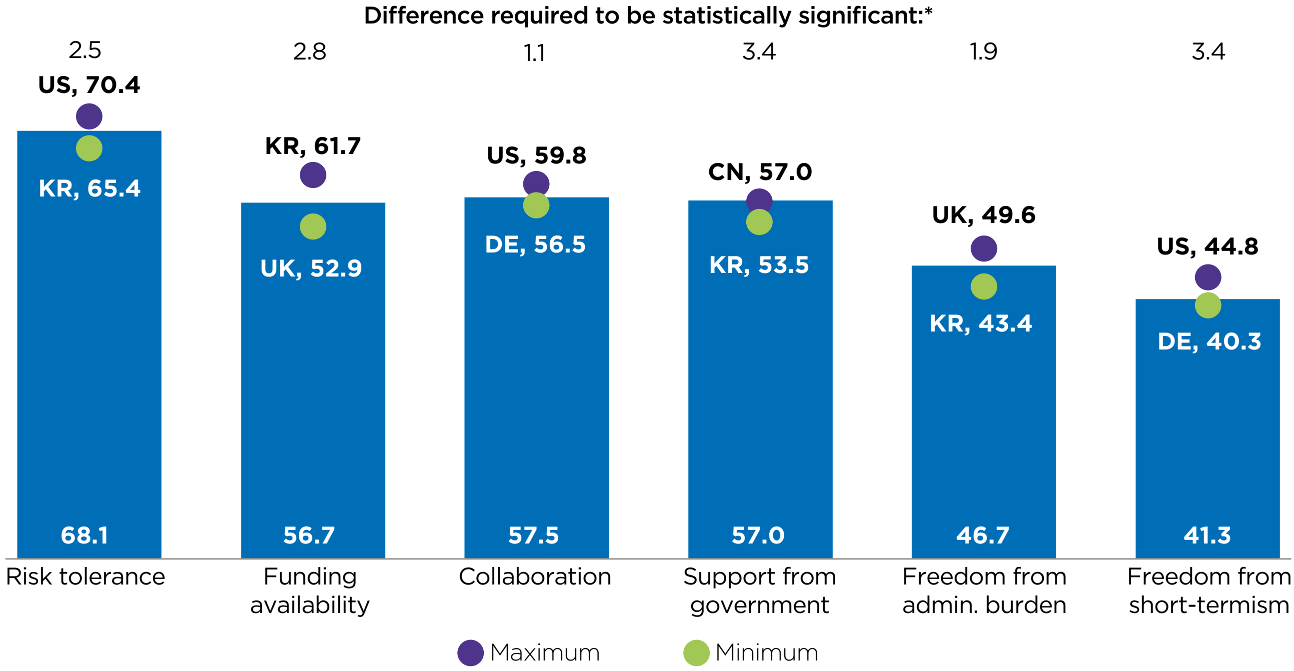
[116] See section 1.2.2 for more discussion on this metric.

5.3.3 Breakdown of scores by country: China

China has the highest Support from Government score, with respondents among the most likely to rate government support for research highly in terms of its overall prioritisation in industrial strategy, as well as elements such as supporting state-run facilities, technology transfer and education for researchers.

Survey respondents report generally being satisfied with the availability of funding for research in China, however the fact that the country's R&D spending to GDP ratio is one of the lowest among our seven countries weighs down on this metric.

Fig. 21: Pulse Check scores by factor for China against the minimum and maximum across all countries



Source: Oxford Economics

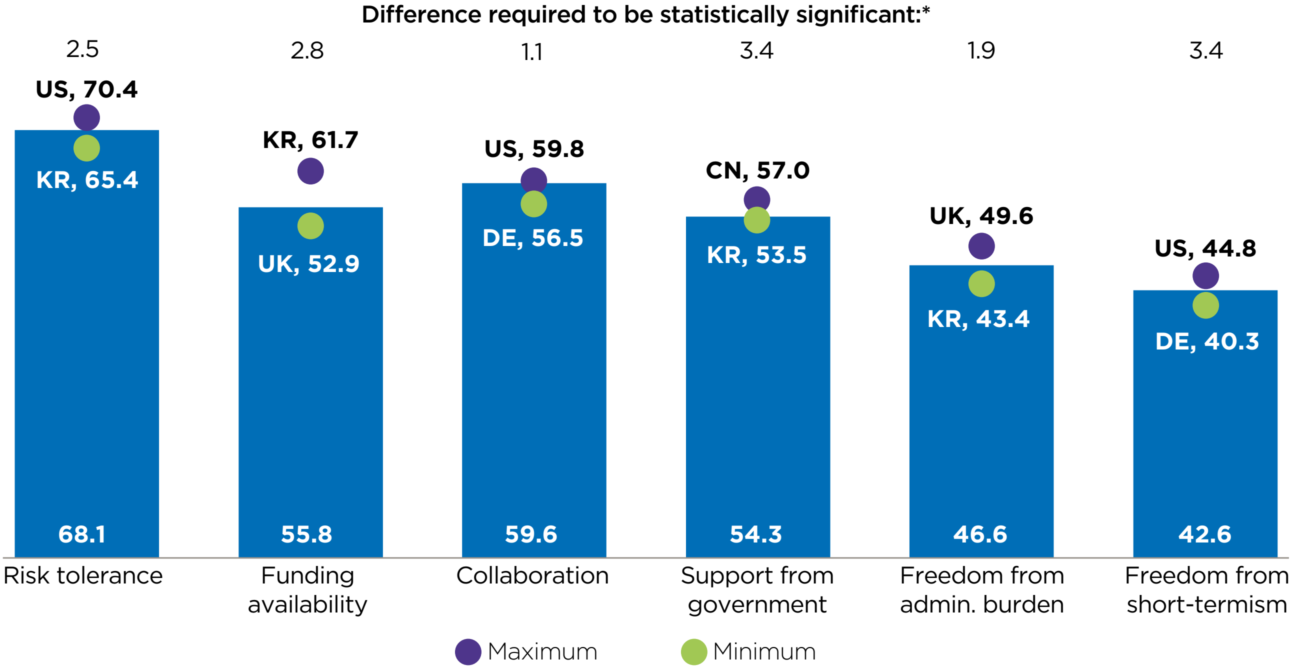
*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

5.3.4 Breakdown of scores by country: France

France had some conditions that were relatively supportive to research and others that were less so. For instance, respondents reported among the lowest levels of research outsourced to third parties. This helped to boost the Collaboration & Outsourcing factor towards the top of the rankings.

One factor weighing down on the country's overall Pulse score was the availability of funding, which respondents reported as lower than in some other countries. For instance, the country spends among the lowest amounts on R&D relative to GDP out of our seven focus countries. Another was the perceived support from government, with respondents from France among the most likely to describe the level of priority given to R&D within the government's overall industrial strategy as "not enough".

Fig. 22: Pulse Check scores by factor for France against the minimum and maximum across all countries



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

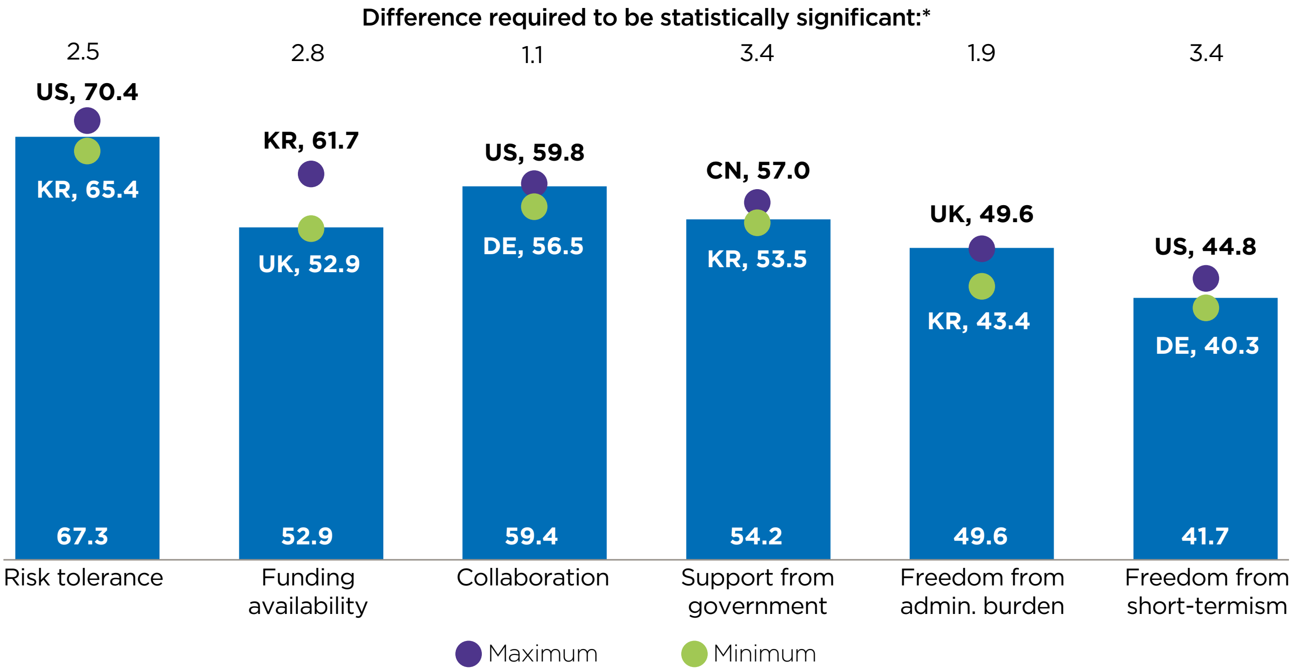
5.3.5 Breakdown of scores by country: United Kingdom

The UK's Pulse Check score is weighed down by weaker environmental factors in some areas. For instance, the availability of funding in the UK is less than in other countries, weighed down by the fact that the country spent just 1.7% in total on R&D as a share of GDP, far below 4.5% in South Korea and 3.3% in Japan. Our survey respondents were also the most likely to report that private sector funding for experimental development was inadequate, and among the most likely to report that both private and public sector funding for applied research was inadequate.

Another negative factor is that researchers in the UK were among the least likely to collaborate with others outside their organisation, which our study has identified as a factor that weighs on research productivity.

However, there were bright spots: the UK had the highest Freedom from Administrative Burden score, with relatively few respondents reporting a "substantial" or "complete" reduction of their research time due to administrative tasks.

Fig. 23: Pulse Check scores by factor for the UK against the minimum and maximum across all countries



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

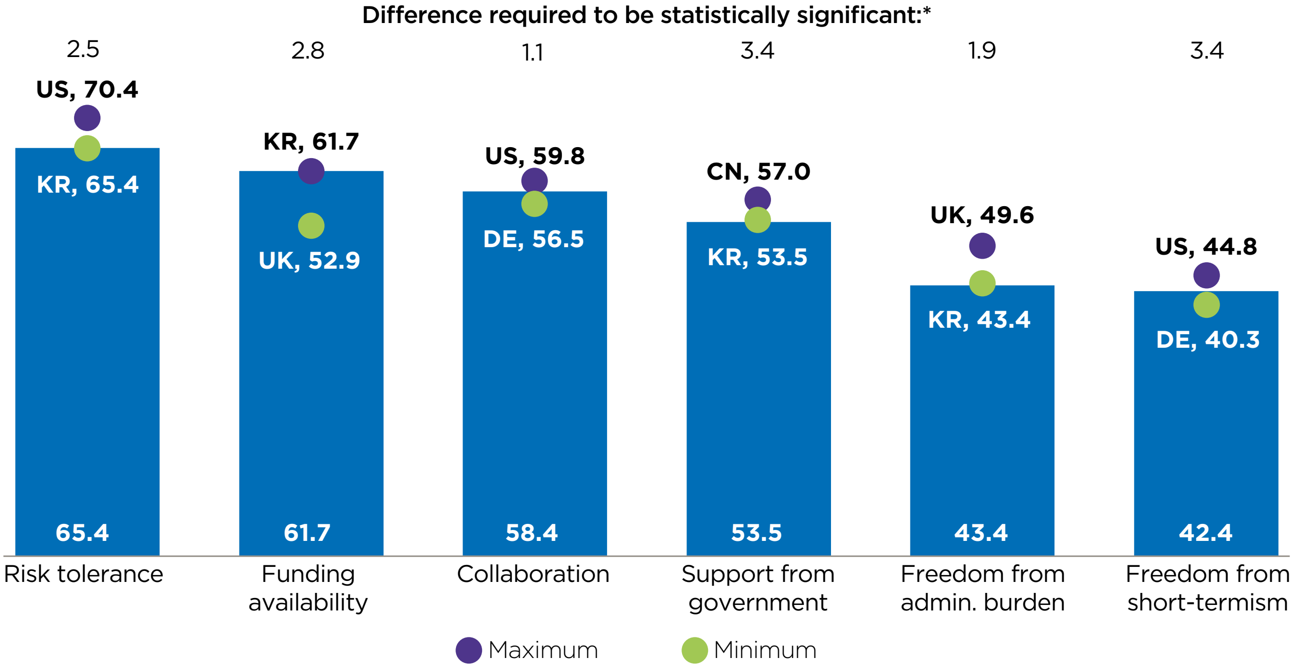
5.3.6 Breakdown of scores by country: South Korea

As one of the lowest-scoring countries on the Pulse Check, our survey respondents suggest that environmental conditions for research in South Korea are not as supportive as other countries in a number of key areas.

This includes respondents in South Korea being the most likely to say that the burden of administrative duties substantially or completely reduced their time available for research. Respondents also believe that the country's government does not adequately prioritise scientific R&D as part of its industrial strategy, as well as scoring the lowest for risk tolerance, with respondents in particular among the most likely to report that allowing projects to act in an agile way towards new information is "strongly discouraged".

One area boosting South Korea's score however is the availability of funding, with the country spending the equivalent of 4.7% of its GDP on R&D—by far the most of any of our focus countries, and indeed the highest of any major OECD country.

Fig. 24: Pulse Check scores by factor for South Korea against the minimum and maximum across all countries



Source: Oxford Economics

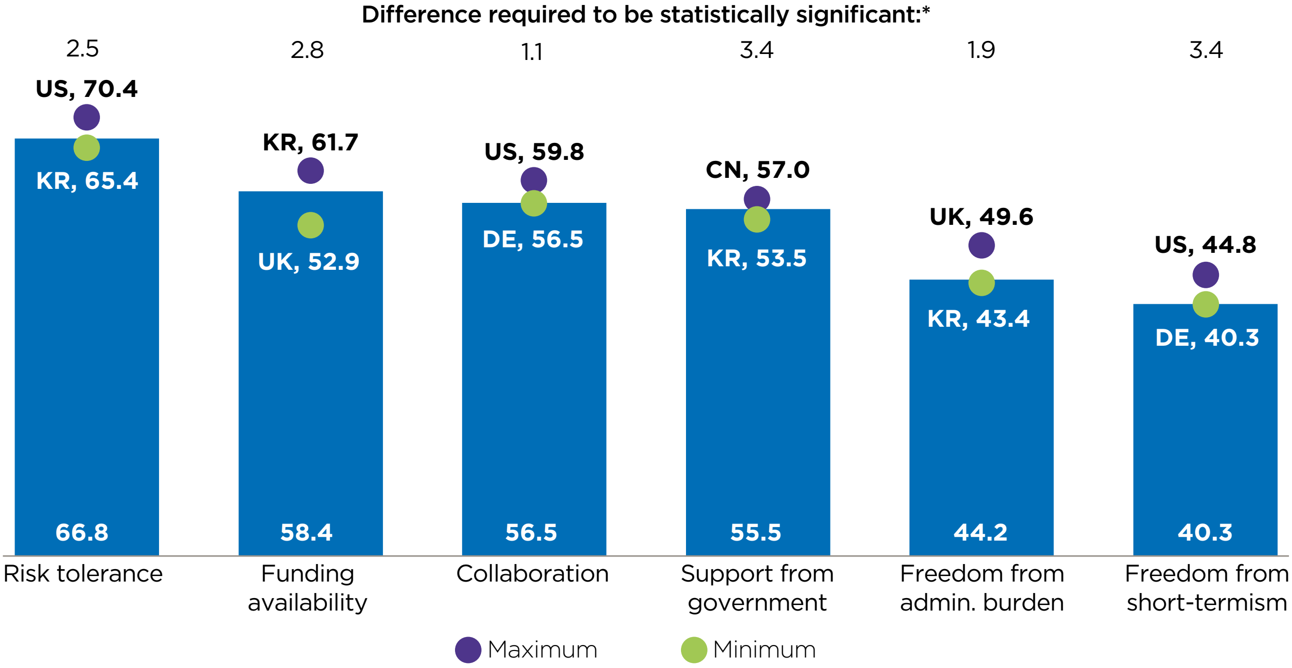
*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

5.3.7 Breakdown of scores by country: Germany

Respondents in Germany were among the most likely to report that the burden of administrative duties they faced "substantially" reduced the time they had available for research. Researchers also reported a relatively high level of risk aversion at their organisations: in particular they were one of the most likely to say that being first to market in new areas was discouraged. Respondents also reported the highest share of budgets being spent with third parties, with evidence suggesting that outsourcing weighs on research productivity. Germany also scored lowest on the Freedom from Short-termism factor, with respondents among the most likely to report that average research life cycles were "very short-term" (0-2 years) and among the most likely to report that pressure from management to produce results as soon as possible was meaningfully detrimental to research.

One area that was more supportive to the research environment was the availability of funding, boosted by the relatively high share of total R&D spending in Germany relative to the size of its economy.

Fig. 25: Pulse Check scores by factor for Germany against the minimum and maximum across all countries



Source: Oxford Economics

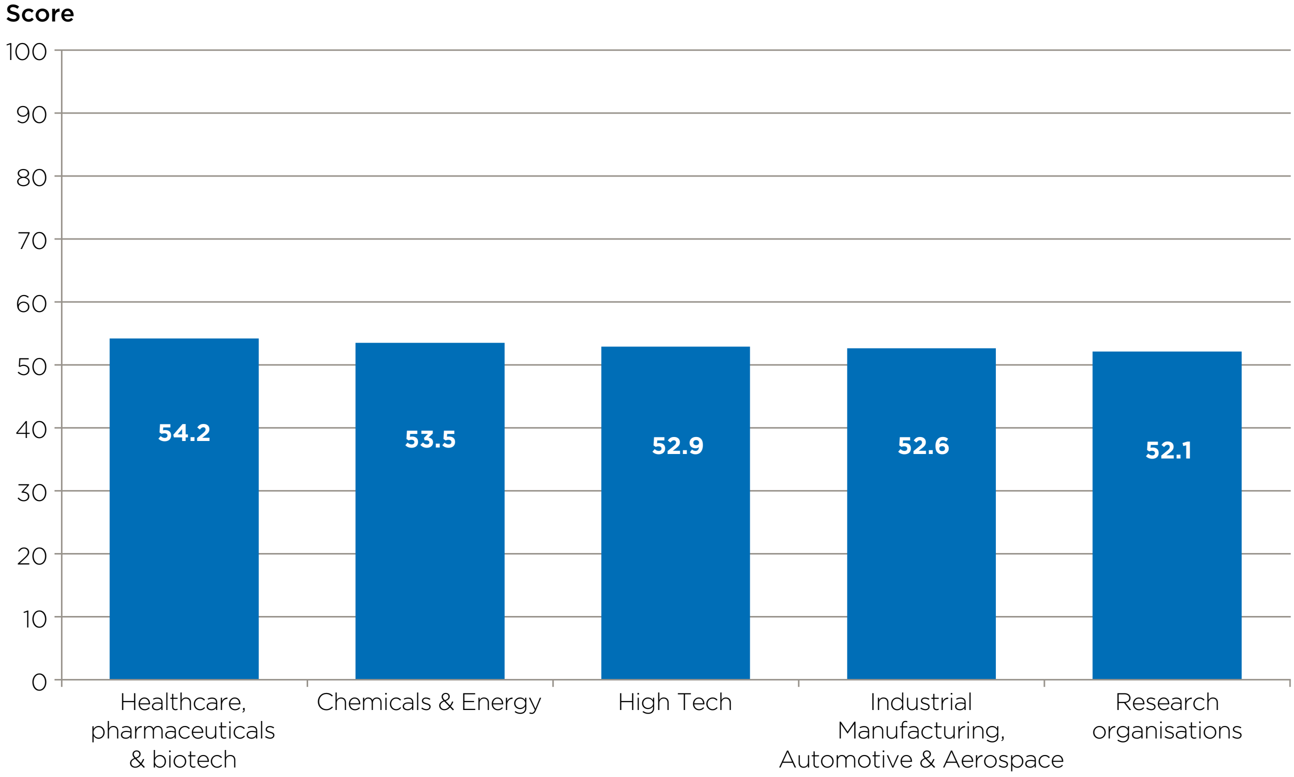
*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

5.4 MAPPING THE STATUS OF PRODUCTIVITY ENABLERS ACROSS INDUSTRIES

We also mapped the structure of the Pulse Check across the business sectors we have focused on in this report, as illustrated in the chart below.

Once again, the readings for each industry are similar.[117] We provide some insight into the results driving each below.

Fig. 26: Overall Pulse Check results split by industry



Source: Oxford Economics

[117] For an industry to report a significant difference from another industry across all six factors, an overall score differential of at least 2.2 points would be seen, just about surpassing even the difference between the highest and lowest industry scores. For more information on the Pulse Check, see Appendix 4.

5.4.1 Healthcare, pharmaceuticals and biotechnology

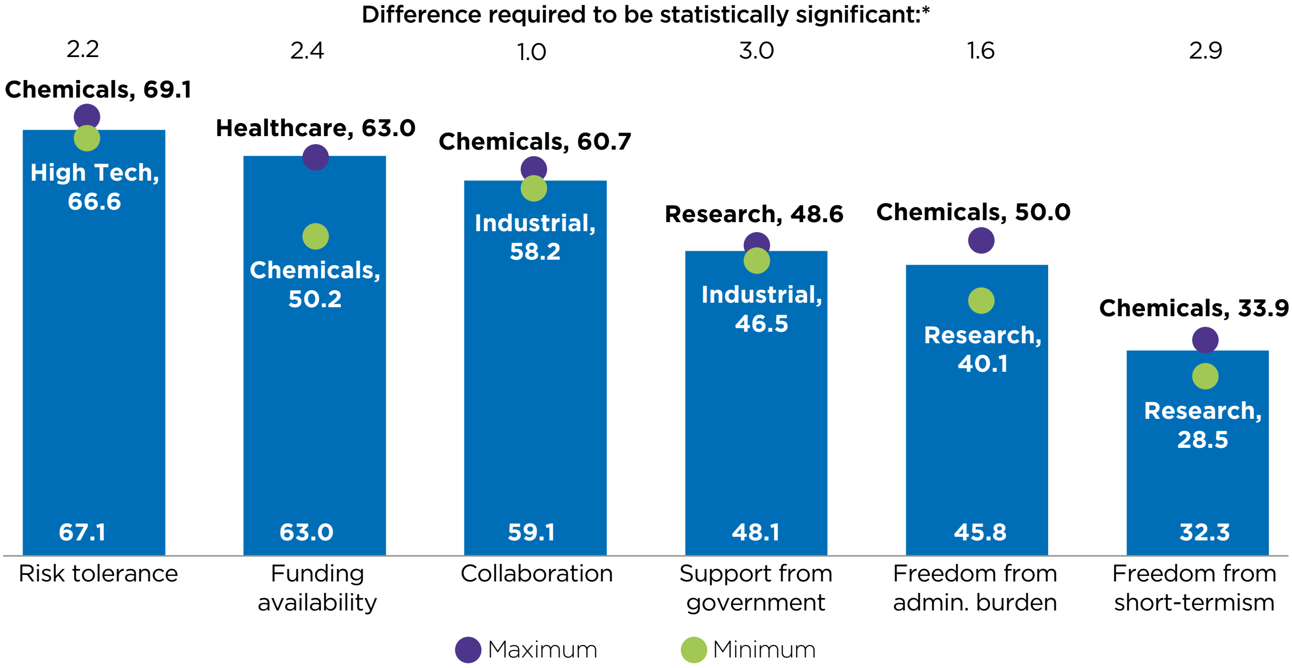
The healthcare, pharmaceutical and biotechnology sector topped the Pulse Check results by industry, with a score boosted by supportive environmental conditions for research across several factors.

For instance, funding in the sector was relatively available: the sector spent more in 2018 on R&D as a share of its economic output than the other industries we have analysed, and respondents were more likely than in other sectors to report that government funding for experimental development was "more than adequate".

Respondents were also more likely to report that research cycles in the sector were "fairly long term" (5-10 years), highlighting how short-termism may be less of an influencing factor than elsewhere in the economy.

However one factor reducing the sector's Pulse Check score was the burden of administrative duties. Respondents were among those most likely to report that this reduces the time they have available for research "completely". Another factor was that firms in the sector outsource a relatively high proportion of their R&D budgets with third-party firms, which we have found as being linked to lower research productivity.

Fig. 27: Pulse Check scores by factor for businesses in the healthcare, pharmaceuticals and biotechnology sector against the minimum and maximum across all sectors



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

5.4.2 Chemicals and energy

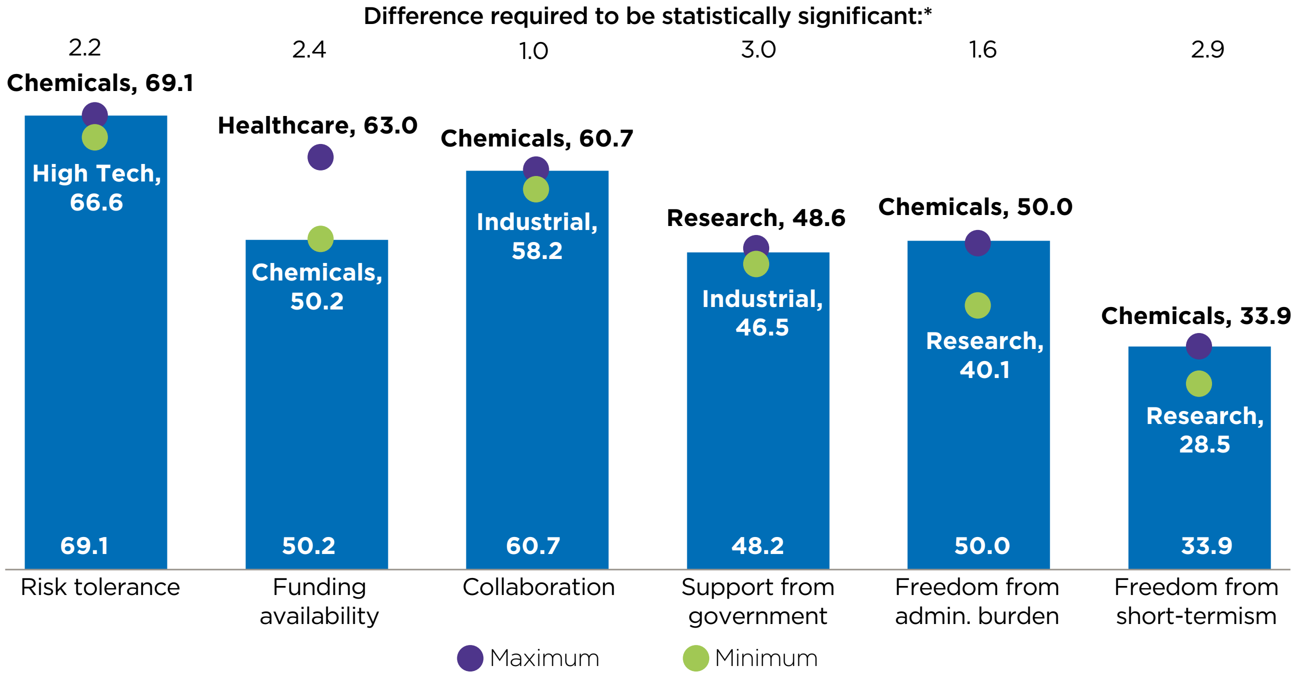
Environmental conditions were felt as relatively supportive in the chemicals and energy sector across many of the Pulse Check elements.

For instance, respondents in the sector were among the least likely to say that their industry was risk averse, particularly in aspects such as allowing researchers rather than business managers to run projects, allowing and funding longer-term projects, and being first to market in new areas of research.

The industry was also among the least likely to say that administrative duties significantly reduced time available for research; were among those outsourcing the least research to third parties, and were the most likely to describe funding cycles as "very long term" (over ten years).

However one factor weighing on the sector's overall Pulse Check score was the availability of funding. The sector spends a relatively low amount on R&D relative to its GDP contribution, and respondents were among those most likely to report inadequate government funding in applied research.

Fig. 28: Pulse Check scores by factor for businesses in the chemicals and energy sector against the minimum and maximum across all sectors



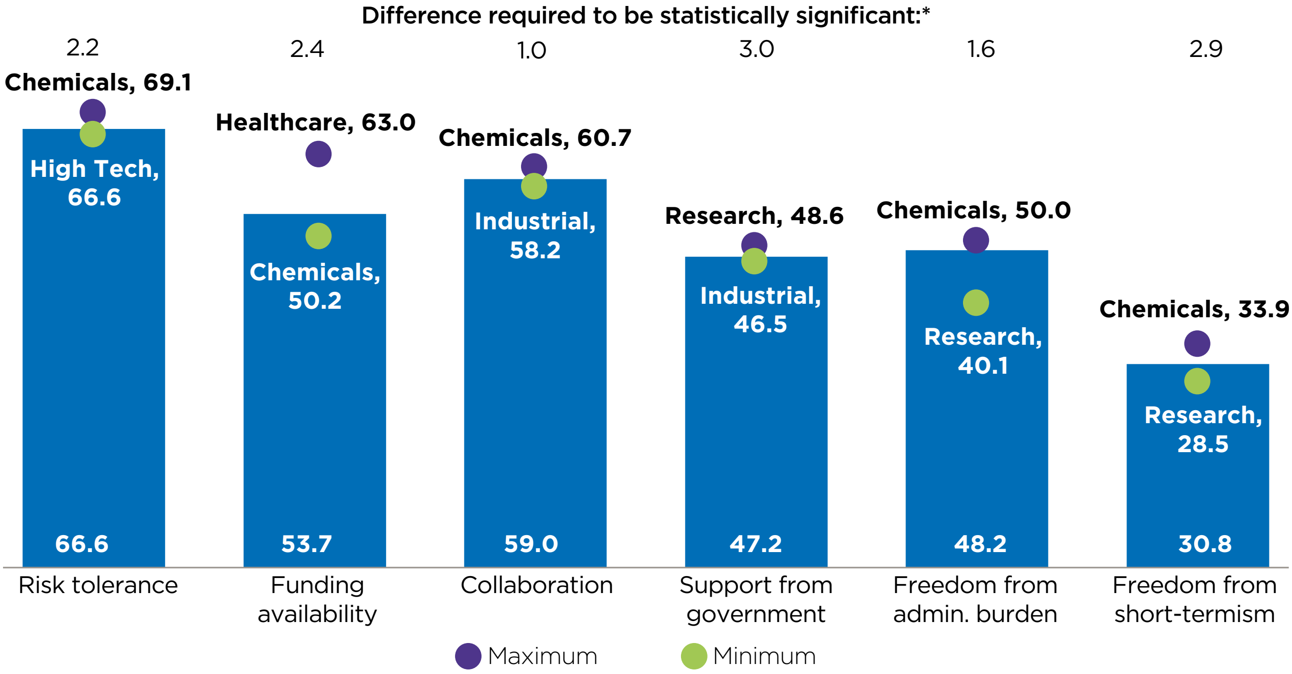
Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

5.4.3 High tech

In the middle of the Pulse Check results is the high tech sector. Driving this result for the sector are factors such as respondents being among the most likely to report risk aversion, particularly in aspects such as allowing projects to react in an agile way to new developments, and developing new areas of research. Survey respondents in the high tech sector were also among the more likely to describe their research and funding cycles as shorter. However one factor boosting the sector's overall score was the relatively limited prevalence of burdensome administrative duties, where the sector scored around the middle of the rankings.

Fig. 29: Pulse Check scores by factor for businesses in the high-tech sector against the minimum and maximum across all sectors



Source: Oxford Economics *minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

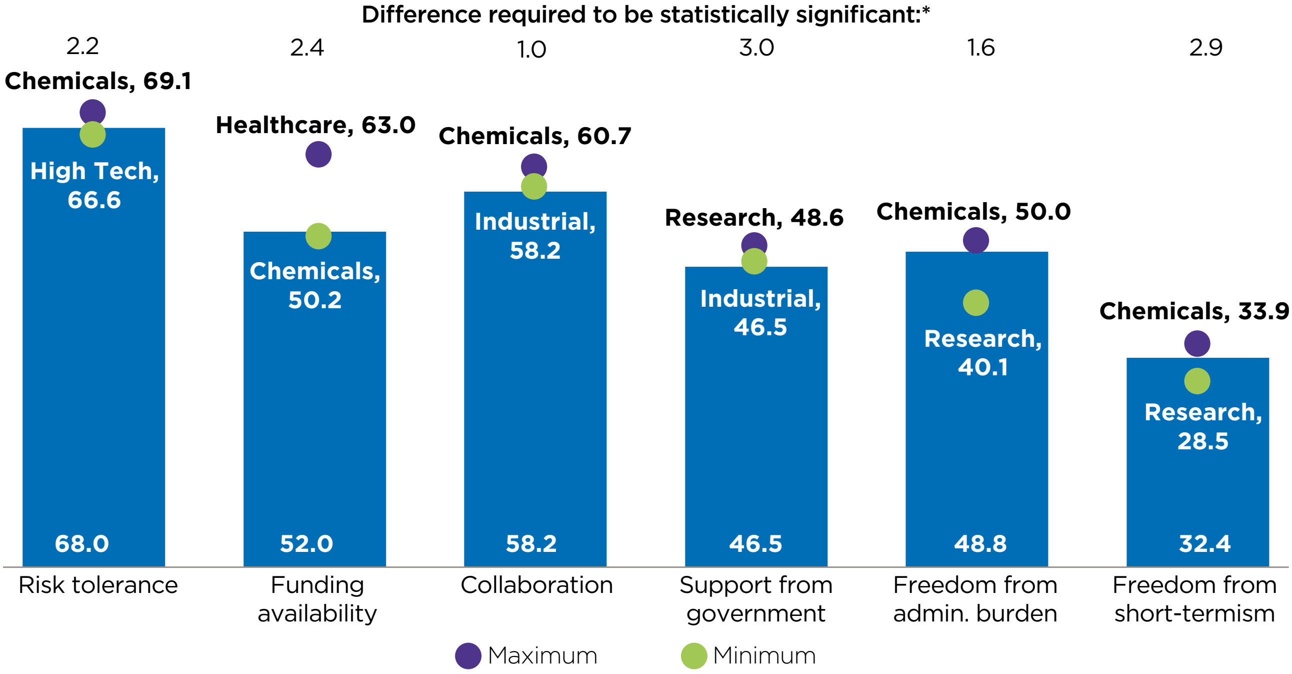
5.4.4 Industrial manufacturing, aerospace and automotive

Towards the lower end of the Pulse Check rankings, the industrial manufacturing, aerospace and automotive sector has relatively supportive conditions for research in some areas, and less so in others.

One particularly supportive area was the prevalence of relatively long research cycles: respondents in the sector were among the most likely to report these as being "fairly long-term" (5-10 years).

One area however where the sector had less supportive conditions was in its view of government support: our survey respondents in this sector were by far the most likely to view the extent to which their government prioritised scientific R&D as part of its industrial strategy as inadequate, at 29% of responses compared to an average of 22% across the other three sectors of focus. Respondents in the sector were also more likely than those in other areas to feel that government R&D funding was inadequate across all three stages of research.

Fig. 30: Pulse Check scores by factor for industrial manufacturing, aerospace and automotive against the min. and max. across all sectors



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.

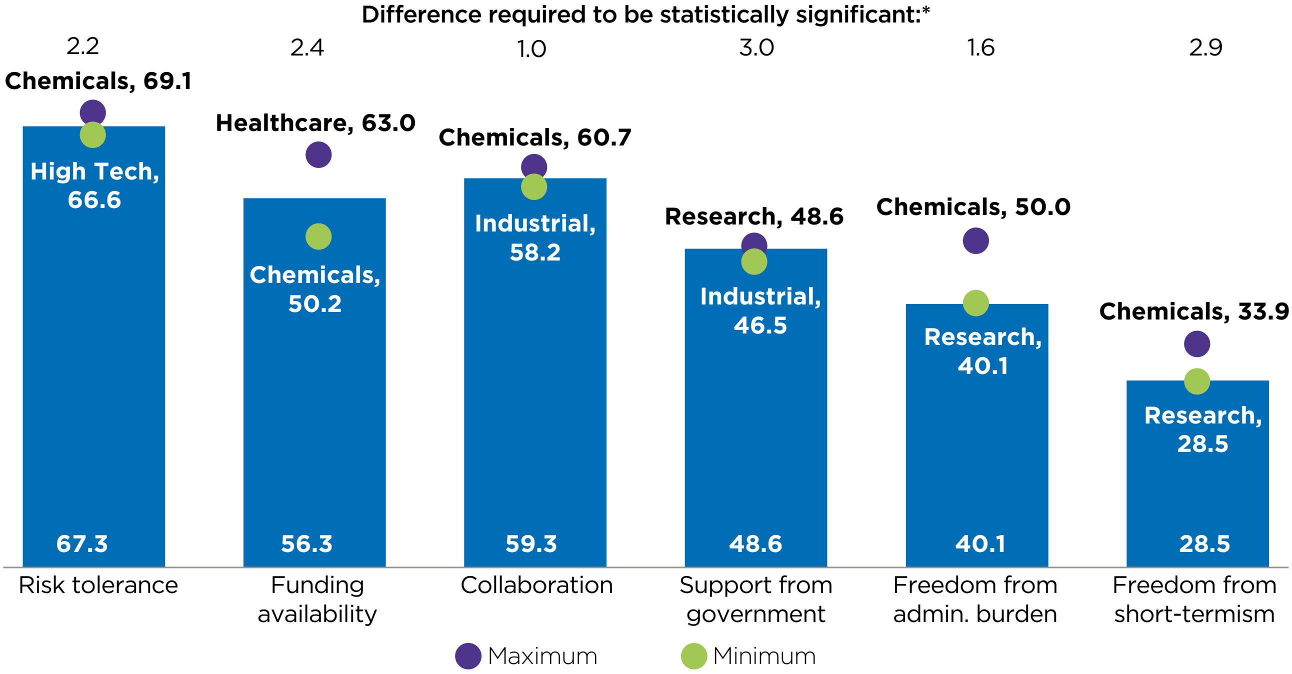
5.4.5 Research organisations

Areas where the research organisation sector reported less supportive conditions were in short-termism and the burden of administrative duties. Respondents from research organisations were the most likely to describe both funding cycles and research cycles as "very short" (up to two years). The sector was also much more likely to describe administrative duties as reducing time available for research "substantially" (34% of respondents vs. 18-24% across other sectors) or "completely" (10%, vs. 3-6%).

However there were some bright spots, with respondents reporting a more supportive environment for research in areas such as the prevalence of collaboration and perspectives on the supportiveness of government. Research organisations were the most likely to collaborate with other organisations, and in particular with domestic and overseas universities, which helped to boost the sector's score in this area. However, this score was weighed down by spending more of their budgets with outsourced research organisations than any other sector.

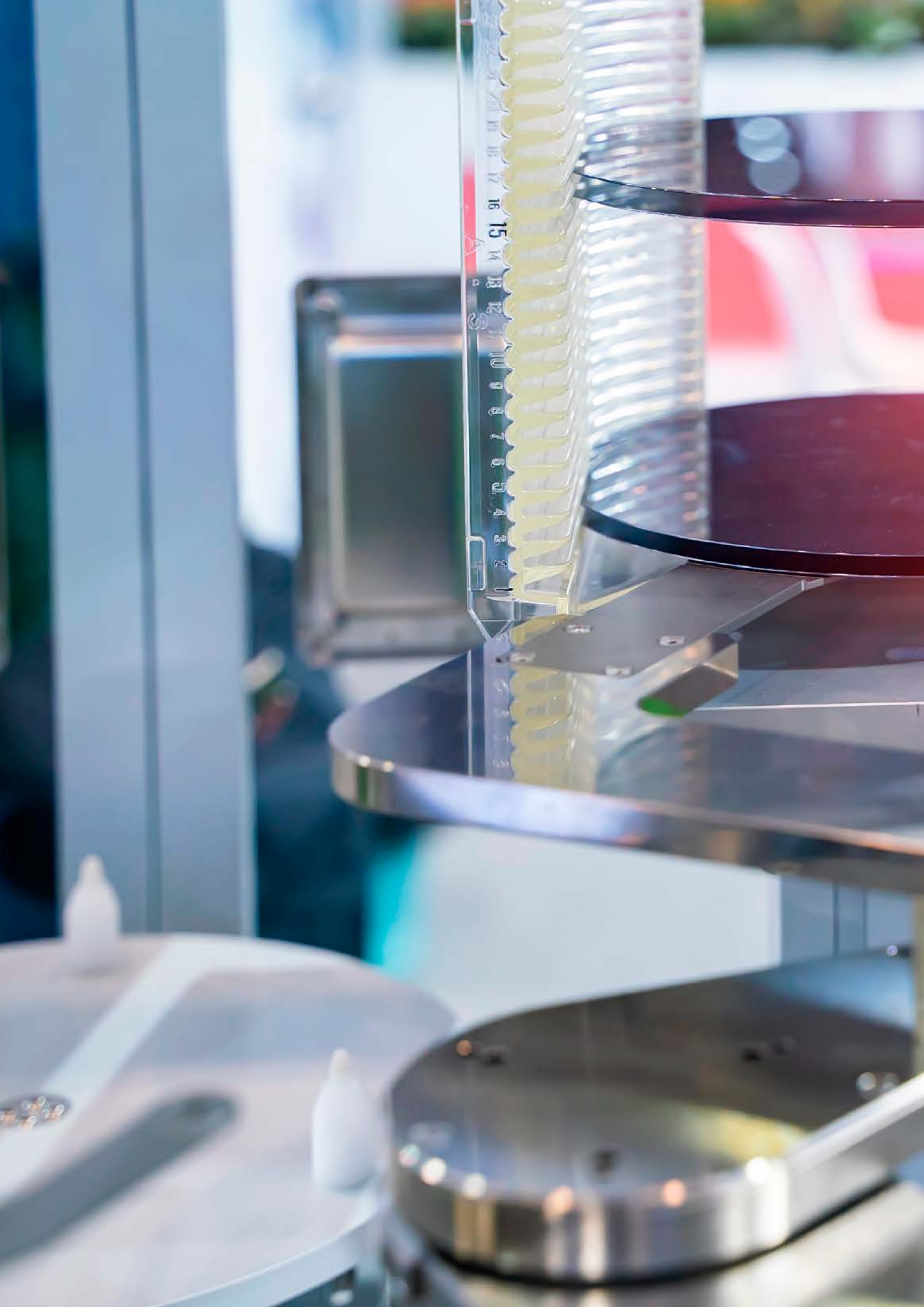
Research organisations also reported having relatively favourable views of the support that government provides. In particular, respondents reported strong support from the government in the form of tax incentives, providing adequate funding and additional financial incentives in the form of prizes.

Fig. 31: Pulse Check scores by factor for research organisations against the minimum and maximum across all sectors



Source: Oxford Economics

*minimum difference in scores required for statistical signifiance. For more information see Appendix 4.



APPENDIX 1: INTERVIEW AND WORKSHOP PARTNERS

We interviewed 25 experts in R&D, including scientific researchers, economists, industry association representatives and policy experts. These interviewees are given in the table below. Job titles and organisation affiliation reflect those at the time of the interview in mid 2020.

Organisation	Country	Interviewee(s)	Job title(s)
Association for Innovation, Research and Technology Organisations (AIRTO)	UK	Steve Yianni; Prof. Richard Brook; Peter Oakley	President; Vice President; Government affairs lead
Centre for Process Innovation	UK	Graham Hillier	Former Director of Strategy and Futures
Nesta	UK	Albert Bravo-Biosca	Director, Innovation Growth Lab
Centre for Science and Policy	UK	Christopher Haley	Policy Fellow
Wellcome Trust	UK	Philip Jordan	Partner, Innovations
Major global aerospace and defence company	UK	*Interview given off the record*	*Senior technology director*
University of Manchester	UK	Prof. Richard Jones	Professor of Materials Physics and Innovation Policy
National Research Council of Italy	Italy	Prof. Giovanni Abramo	Head, Laboratory for Studies in Research Evaluation
Iowa State University	USA	Prof. Joshua Rosenbloom	Chair, Department of Economics
George Mason University	USA	Prof. Tyler Cowen	Professor of Economics
University of Oxford	UK	Prof. Stuart Conway	Professor of Organic Chemistry
HR Wallingford	UK	Bruce Tomlinson	CEO
Materials Processing Institute	UK	Chris McDonald	CEO
EMD Serono	USA	Julie DeMartino	Senior Vice President, Immunology
MilliporeSigma	USA	Patrick Schneider	Head of Strategy, Business Development and Innovation
Fraunhofer Institute for Solar Energy Systems ISE	Germany	Dr Simon Philipps	Head of R&D Strategy
Tsinghua University	China	Prof. Jin Chen	Director, Research Center of Technological Innovation
National University of Singapore	Singapore	Prof. Albert Hu Guangzhou	Associate Professor, Department of Economics
Brandeis University	USA	Prof. Gary Jefferson	Carl Marks Professor of International Trade and Finance
China Innovation Center of Merck KGaA, Darmstadt, Germany	China	Sophie Sun	Managing Director (Note: has since left the company)
Pitney Bowes	USA	James Fairweather	Chief Innovation Officer
NeoX BioTech	China	Michael Chen	Co-founder and CEO
Chonnam National University	South Korea	Dr.-Ing Jong-Oh Park	President, Korea Institute of Medical Microrobotics
Curesponse	Israel	Dr Seth Salpeter	Co-founder and CTO
Nanyang Technical University	Singapore	Associate Prof. Karthik Kumar	Director, Science and Engineering Research Council, A*STAR
American Association for the Advancement of Science	USA	Aaron Clauset	Science Advances Deputy Editor

We also hosted a workshop for eight R&D experts in Europe and North America. These participants are given in the table below.

Organisation	Country	Interviewee(s)	Job title(s)
Cytiva Life Sciences	USA	Dr Dirk Voelkel	VP, Innovation
Rocky Mountain Biological Laboratory	USA	Ian Billick, PhD	Executive Director
NKT	Germany	Johan Hedlund	R&D Manager
American Chemet Corp.	USA	Dr Colin Anderson	R&D Director
Teraloop	Finland	James Hagerman	eMobility consultant
Northwestern University	USA	Prof. Randall Berry	Chair and John A. Dever Professor, Department of Electrical and Computer Engineering
Max Planck Institute for Innovation and Competition	Germany	Prof. Dietmar Harhoff	Director
VDMA	Germany	Kai Peters	Research and policy advisor

APPENDIX 2: ECONOMETRIC MODELLING DETAILED METHODOLOGY

AIM OF THE ECONOMETRIC MODELLING EXERCISE

The statistical analysis is an important tool that complements the findings from other tools used in the project such as expert interviews or the literature review.

We undertake two types of statistical analysis as both add value in themselves and in combination:

1. **Descriptive statistics** were used to describe trends in variables over time and across industries and the direct associations between variables (correlation), allowing us to paint a high-level picture of trends.

2. **Econometric modelling** is a more advanced statistical technique which goes beyond identifying correlation to help draw causal inference. Well specified models with high quality data were used to develop more precise estimates of the independent relationship between two variables. We identified significant drivers of research productivity and combined these results with descriptive statistics to understand the extent to which that factor has influenced research productivity.

Even though the econometric exercise adds significant value to the study, it faces material challenges with measurement error with regards to quantifying its outputs as well as some factors being inherently unquantifiable due to data constraints. Hence the necessity to have a wide array of tools that, tied together, provide means to assess the relative influence of different drivers of research productivity.

We construct two models to study different types of Research and Development processes: 1) the basic research model, which looks at universities' research productivity and 2) the applied research model, which studies research productivity of firms.

BASIC RESEARCH MODEL

Data sources

For this model, we need information on universities' research outputs and inputs to construct a measure of productivity and additional variables that might be impacting that measure.

We use data from three sources: 1) SciVal, an online tool with worldwide information on research institutions' performance using bibliometrics, 2) the Higher Education Research and Development Survey on R&D expenditures of U.S. colleges and universities published by the National Science Foundation and 3) the National Centre for Education Statistics.

We use SciVal to obtain information on the top 100 academic institutions in 11 fields (e.g. "Arts & humanities, "Life sciences" or "Engineering") in the U.S. by number of publications between 2017-19. Specifically, this tool allowed us to gather data on:

- Number of publications
- Field-weighted citation impact – ratio of citations received relative to the world average for the subject field, publication type and year of publication
- Share of publications the entity has with international, national and institutional co-authorship or single authorship
- Share of publications with corporate or industrial co-authorship

We then used the Higher Education Research and Development survey microdata to obtain information on U.S. universities between 1998 and 2018 on:

- R&D expenditure at the university-field level by:
- Source of funds (government (federal, state and local), industry (both national and international), the university itself and other sources, such as donors and not-for-profit organisations)
- Nationality of the funds (domestic or international)

- Type of costs (e.g. software or wages)
- R&D expenditure by type of R&D at the university level (total and share of it financed by federal government funds)

Finally, we resorted to the National Centre for Education Statistics to create a dummy variable to identify the ownership structure of each university, i.e. whether it is private or public.

The last step was to merge the data from the three sources and obtain a unique unbalanced panel data set of 86 universities and 11 fields between 1998 and 2018.

Model

Some universities and fields may be more productive than others due to time-invariant individual characteristics that may be either observable or unobservable. For example, research in life sciences often requires experiments with significant costs attached whereas research in social sciences is generally less capital intensive. This implies that when the measure of productivity uses expenditure as the input, such fields may display lower values of productivity than others by default.

We suspected that in fact, these individual characteristics could be significantly impacting our regressors and the outcome variable, in which case a fixed effects model would be the most appropriate technique to use. This hypothesis was tested and confirmed by the Hausman test, which compares the consistency of random effects estimators to the less efficient but consistent fixed effect estimators.

Hence, we used a fixed effects model that controls for the average difference of both observed and unobserved factors within universities, fields and years, where the equation is as follows:

$$Y_{it} = \alpha_i + \theta_j + \beta X_{itj} + \varepsilon_{itj} \; for \; i = 1, \ldots, 86, j = 0, \ldots 10 \; and \; t = 1998, \ldots, 2018$$

Where

- Y_{it} is the dependent variable (citation-adjusted number of publications per million of dollar spent on R&D) and *i* = university, *j* = field and *t* = year
- α_i is the unknown constant for each university
- X_{it} is the vector of independent variables (e.g. source of funds)
- β is the matrix of coefficients
- ε_{it} is the error term.

We used a modified version of the Wald test and found groupwise heteroskedasticity, which was corrected by using the robust estimators (*sandwich*).

Results

Our baseline model is identified in Fig. 32. We found that funding by government and industry supported productivity, whereas the university's own funds and other sources did not. This is consistent with existing literature, such as Bolli and Somogoyi's "Do competitively acquired funds induce universities to increase productivity?" (2010), which found positive impacts on productivity for both public third-party funding and private funding. In recent years, we found that the share of government and industry funding have been declining in the U.S., which our modelling suggests can be acting as a drag on research productivity growth.

Additionally, we found that collaboration between academics helped boost productivity and that the effect was stronger with cross-university and international collaboration than for academics within the same university. This reflects some of the existing literature, such as "International collaboration" by Barjak and Robinson (2008), which found that teams with international collaboration published more articles and achieved a higher citation rate than those with no collaboration. Within this finding, the impact was greater for collaboration between universities, including internationally, than within one institution. In the same period, we observed a rising share of papers being produced with international collaboration, and a shrinking share of papers with single authorship in the U.S., which has helped support research productivity.

Fig. 32 also displays four alternative models which were tested for the impact of: the nationality of the funds; the cost structure of universities' R&D spending; the universities' ownership structure and; the role of academic-corporate collaboration. Even though the first hypothesis tested seems to suggest that a higher share of domestic funds is associated with higher research productivity, the number of observations almost halved distorting the results obtained in the baseline scenario. Hence, we are cautious in drawing conclusions from this test. In the remaining tests, we do not find statistically significant relationships.

Fig. 32: Table of results for the baseline model and hypotheses tested

Citation-adjusted publications / R&D expenditure	Baseline model	Hypothesis I	Hypothesis II	Hypothesis III	Hypothesis IV
Constant	0.08	-0.79**	-2.46**	0.15	0.08
Source of funds					
Public	0.54***	0.46	3.11***	0.54***	0.54***
Industry	0.43*	0.05	2.83**	0.43*	0.42*
University	-0.5***	-0.65**	1.99**	-0.50***	-0.49***
Other (reference group)	-	-	-	-	-
Collaboration					
International	0.61***	0.65***	0.66**	0.61***	0.60***
National	0.41***	0.40***	0.26	0.41***	0.40***
Institutional	0.31***	0.09	0.08	0.31***	0.31***
Single author (reference group)	-	-	-	-	-
Domestic funds	NA	1.1**	NA	NA	NA
Cost structure	NA	NA	Non-significant	NA	NA
Ownership structure	NA	NA	NA	Non-significant	NA
Academic-corporate collaboration	NA	NA	NA	NA	Non-significant
University FE	Yes	Yes	Yes	Yes	Yes
Subject area FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Number of observations	**7,826**	**4,156**	**874**	**7,826**	**7,826**

* Significant at 10% level, ** significant at 5% level, *** significant at 1% level

Ideally, we would like our model to take into consideration exclusively R&D expenditure in basic research. However, to be able to have a further breakdown by field, the input used in our productivity measure had to be total R&D expenditure of the university in a given field. Nevertheless, we ran an alternative model where we then included the input measure as a regressor, in this case R&D expenditure in basic research. We also tested a similar model where the input measure used was labour rather than capital, i.e. we substituted R&D expenditure in basic research by the number of R&D personnel of each university (see Hypotheses VI in the figure below).

Fig. 33: Table of results for hypotheses with alternative productivity measure

Citation-adjusted publications	Hypotheses V	Hypotheses VI
Constant	3.74***	3.59***
Source of funds		
Public	0.46**	0.44**
Industry	-0.06	-0.23
University	0.34*	0.31*
Other (reference group)	-	-
Collaboration		
International	0.82***	0.81***
National	0.57***	0.59***
Institutional	0.34***	0.34***
Single author (reference group)	-	-
R&D personnel	NA	0.04**
R&D basic research spending	0.01	NA
University FE	Yes	Yes
Subject area FE	Yes	Yes
Year FE	Yes	Yes
Number of observations	**4,959**	**4,863**

* Significant at 10% level, ** significant at 5% level, *** significant at 1% level

The field breakdown in the dependent variable allowed for some additional tests whereby we explored if the impact of the drivers varied between scientific and non-scientific fields. We classified the following as scientific fields: "Computer sciences", "Engineering", "Health sciences", "Other life sciences" and "Physical sciences". All other were classified as non- (e.g. "Psychology" or "Arts and humanities").

We found that both the positive impact of the share of government funding and the negative impact of the share of university funding in research productivity are larger for non-scientific fields. Furthermore, we found that relative to single authorship:

- the impact of the share of international collaboration is associated with an increase in scientific research productivity only for scientific fields;
- the impact of the share of national collaboration is associated with an increase in scientific research productivity, with a larger impact on scientific fields;
- the impact of the share of institutional collaboration is associated with an increase in scientific research productivity for non-scientific fields and a decrease for scientific fields.

Uses of this research

This exercise allowed us to explore different factors that could be playing a role in the trend of research productivity of academic institutions observed in the last two decades. It identifies some statistically significant relationships between explanatory variables and our outcome variable, all else equal.

We used these insights combined with descriptive statistics on the trends of those drivers to analyse the direction in which these factors have been impacting research productivity. For instance, we found that collaboration is associated with a higher level of research productivity all else equal (particularly international and national collaboration). We then conducted some descriptive statistics and found that in the U.S., international collaboration has been increasing overall which has helped support research productivity.

These results were also used to inform our survey design where we further introduced and explored questions regarding sources of funds and collaboration.

APPLIED RESEARCH MODEL

Data sources

This model analyses research productivity of applied research in the United States, United Kingdom and Germany. We resort to Orbis for firm level data between 2011 and 2017 on the number of patents and firms R&D expenditure which allows us to create a measure of applied research productivity – number of patents filled per million of R&D spending. This dataset also provides firm level data on annual sales, number of employees, cost of employees, assets, intangible assets, cash flow and capital. Orbis' provided us with more than 1,000 firms, whose patent output covered 7% of total patents in those countries in that period.

We also use industry level data from business surveys conducted in each country – the US Business Research & Development Survey and the National Patterns of R&D Resources, the Business Enterprise on Research and Development Survey UK and the statistics on research and development in the economic sector in Germany. These surveys provide information by industry on:

- R&D employment
- R&D funding by source (e.g. government)
- External R&D spending – outsourcing
- Spending by type of R&D
- R&D cost structure (e.g. share of capital costs out of all)

Model

We run a series of statistical tests to identify the correct model specification for our chosen measure of scientific research productivity in the applied research field. Among our key findings, we found that the firm fixed effects played an important role in explaining the observed heterogeneity in the number of patents filled per million of R&D spending across the three countries which were considered in our study. Furthermore, we also found our dependent variable to exhibit a lot of persistence over time, this suggests that the use of a dynamic model is appropriate to account for this important feature of the data. Specifically, the equation we use can be described as follows:

$$Y_{it} = \alpha_i + \theta_j + Y_{it\text{-}1} + \beta X_{it} + \varepsilon_{it}$$
$$f\,or\ i = 1, \ldots, 10000,\ and\ t = 2011, \ldots, 2017$$

Where

- Y_{it} is the dependent variable (number of patents filled per million of dollar spent on R&D) and *i* = firms and *t* = year
- α_i is the unknown constant for each firm
- X_{it} is the vector of independent variables (e.g. source of funds)
- β is the matrix of coefficients
- ε_{it} is the error term.

The inclusion of the lagged dependent variable as an additional explanatory variable makes our model dynamic. Statistically, unless one uses a specialised estimator, the coefficient on the lagged explanatory variable is likely to be biased by virtue of this variable being correlated with the error term. To correct for the presence of this bias, we employ the Blundell and Bond estimator (also known as System GMM).

Dynamic panel models have become increasingly popular in many areas of economic research, and their use has provided new insights. Using dynamic panel models allows us to find overall (long-run) coefficients for the explanatory variables as well as the contemporaneous (or short-run) ones.

The advantages of dynamic models include:

- controlling for the impact of past values of scientific research productivity on current productivity;
- estimation of overall (long-run) and contemporaneous (short-run) effects; and
- use of past values of explanatory variables as instrumental variables to mitigate the bias due to endogeneity.

Results

Our model results are presented in Fig. 34. Specifically, we ran 3 models. First, we run a baseline model using all the three countries included in our sample, namely the US, the UK and Germany. Second, we run two subsequent models using the US and UK samples sequentially testing for additional variables that are missing for Germany. All our models pass the Hansen robustness tests suggesting that the results are fit for purpose. Among our key findings, we consistently identify, across all three models, a negative association between firm size and scientific research productivity. This finding is in line with Bonaccorsi and Daraio (2005) who find similar results in their study exploring the relationship between firm size and agglomeration effects on public research productivity. We also find a negative association between our measure of industry competition and scientific research productivity.

Testing additional variables sequentially, we find a statistically insignificant association between the share of funding which is received from the government and scientific research productivity. Furthermore, we find a negative association between the share of funding sourced domestically and scientific research productivity. The share of spending devoted to development is positively associated with scientific research productivity, this is in line with findings from Ponds et al. (2010). We find a negative association between the share of capital (all non labour) costs in total costs and scientific research productivity. This is similar to findings from Griffith et al. (2001).

Finally, we find a negative association between outsourcing research and development and scientific research productivity. This finding is in line with Shin et al. (2016) who find similar results when looking at R&D and firm performance in the semiconductor industry.

Fig. 34: Baseline Models Results

Citation-adjusted publications / R&D expenditure	Baseline model	Model A (US, UK)	Model B (US, UK)
Constant	2.31 ***	3.25 ***	3.43 ***
Lag dependent variable	0.53***	0.38 ***	0.36 ***
Size	-0.13***	-0.15 ***	-0.18 ***
Industry competition	-0.20 ***	-0.27 ***	-0.30 ***
Share of government funding	NA	Non-significant	Non-significant
Capital share of costs	NA	- 0.56 **	-0.37 **
Share of funding from domestic sources	NA	Non-significant	NA
Share of spending on development	NA	Non-significant	0.64 **
Outsourcing	NA	NA	-0.03 **
Number of observations	**4,208**	**3,108**	**3,108**
Hansen test	**Passed**	**Passed**	**Passed**

* Significant at 10% level, ** significant at 5% level, *** significant at 1% level

APPENDIX 3: SURVEY METHODOLOGY

Oxford Economics was commissioned by Merck KGaA, Darmstadt, Germany to field a survey of 3,500 individuals who have substantial responsibility for / oversight of research projects at their organizations.

Fieldwork took place between November 2020 and February 2021 and was conducted primarily via computer-assisted telephone interviewing.[118] Respondents were also given the opportunity to see the written survey on-screen as they reported answers to a moderator over the phone.

The questionnaire was developed in Autumn 2020, following the literature review, in-depth interviews, and econometric analysis described above. Questions were built to test hypotheses formed during that stage of the research program.

Respondents represent seven countries, five industries, and a range of organization sizes and types. Further details on the sample's demographic profile are noted below.

SURVEY DEMOGRAPHIC BREAKDOWN

Respondent role

To qualify, respondents must report substantial responsibility for or complete oversight of research projects at their organization. Targeted titles include:

- Heads or senior members of research institutes
- Heads or senior members of policy think tanks
- Heads or senior members of R&D departments in corporates
- CEOs or heads of R&D of start-ups
- Heads or senior members of research projects in academic institutions

Country

500 respondents in each of the following countries:

- China
- France
- Germany
- Japan
- South Korea
- United Kingdom
- United States

Industry

700 respondents (100 per country) across five industry groupings. These were targeted according to the standard industrial classifications used in calculating economic accounts, as follows:

- **Chemicals and Energy**, including:
  - Manufacturing of chemicals, rubber, plastic, basic metals and mineral products
  - Electricity, gas, steam and other utilities
- **Healthcare**, including:
  - Manufacturing of pharmaceuticals
  - Manufacturing of dental and medical instruments and supplies
- **High Tech**, including:
  - Manufacture of computer, electronic, electrical and optical equipment
  - Software publishing
  - Telecommunications
  - Computer programming, consultancy and related activities

[118] A telephone surveying technique in which the interviewer follows a script provided by a software application.

- **Industrial Manufacturing and Automotive**, including:
  - Manufacturing of fabricated metal products, machinery and equipment
  - Manufacturing of motor vehicles and other transport equipment (including aerospace)
- **Research**, including:
  - Research and experimental development on natural sciences and engineering
  - Higher education

Stage of research

Natural fallout (i.e. no demographic quotas):

- Basic research – 29%
- Applied research – 45%
- Experimental development – 26%

Organisation size

Natural fallout (i.e. no demographic quotas):

- 30% under $99.9 million
- 37% $100 million to $999.9 million
- 30% $1 billion to $49.9 billion
- 3% $50 billion+

Annual research budget

Natural fallout (i.e. no demographic quotas):

- 15% under $1 million
- 49% $1 million to $24.9 million
- 21% $25 million to $100 million
- 16% over $100 million

Organisation type

Natural fallout (i.e. no demographic quotas):

- Publicly traded for-profit company – 51%
- Privately owned for-profit company – 29%
- Academic institution – 15%
- Government, non-profit organizations, and public-private consortiums – 6%

All survey results reported in this study were tested for statistically significant differences at the 95% or 90% confidence level.

APPENDIX 4: DETAILED METHODOLOGY OF SCIENTIFIC RESEARCH PRODUCTIVITY PULSE CHECK

COMPONENTS OF THE SCIENTIFIC RESEARCH PRODUCTIVITY PULSE CHECK

The Pulse Check is made up of the individual factors set out below.

Freedom from short-termism

This factor was selected for inclusion in the Index as it was highlighted by participants in our expert workshop as one of the top barriers to productivity and mentioned as important in several of expert interviews.

Data for this element on the timescales actually faced by respondents was taken from the survey questions "How long are most <u>research</u> cycles in your department?" and "How long are most <u>funding</u> cycles in your department?".

Data on other time pressures imposed on researchers were taken from the survey questions "Is pressure to produce results within a shortening timeframe a substantial barrier to research at your organiation?" and "Is pressure from management to produce results as soon as possible meaningfully detrimental to scientific research productivity?".

Level of risk tolerance

This factor was selected for inclusion in the Index as it was highlighted by participants in our expert workshop as one of the top barriers to productivity and mentioned as important in several of expert interviews.

Data for this element was taken from our survey questions which asked "To what extent do senior managers at your organization OR at your funders' organizations support and facilitate the following?"

- Taking on additional risk to conduct research in unexplored areas
- Allowing and funding longer-term projects
- Developing new areas of research/being first to market in a new area
- Allowing projects to react in an agile way to new requirements/new information
- Collaborating with external researchers
- Publishing negative results to help others in the field
- Allowing researchers to run projects rather than business/finance managers

Extent of government support

This factor was selected for inclusion in the Index as it was a recurring theme of importance through our expert interviews.

Data for this element was taken from our survey questions which asked "To what extent does your country's government prioritise scientific research and development as part of its industrial strategy?" and "How well does your national government support scientific research in terms of the following?"

- Providing adequate funding
- Strategizing around particular focus areas and distributing funding/resources accordingly
- Supporting state-run research facilities and start-up incubators
- Ensuring quality of education/training for researchers (e.g., PhD programs)
- Supporting technology transfer (e.g., helping universities to monetise innovations)
- Providing tax incentives
- Providing additional financial incentives or prizes around successful innovation

Freedom from administrative burden

This factor was selected for inclusion in the Index as it was a recurring theme of importance through our expert interviews.

Data for this element was taken from our survey question which asked "To what extent does the burden of administrative duties reduce the time that you and your team have available for research?".

Extent of collaboration and outsourcing

This factor was selected for inclusion in the Index as our econometric modelling and literature review found a statistically significant relationship between these factors and the productivity of scientific research, although this wasn't necessarily reflected in the views given by survey respondents.

Data for this element was taken from our survey questions which asked "Roughly what proportion of your department's overall research budget is spent with third-party research organisations?" and "Roughly what proportion of your department's research projects include significant collaboration with the following types of third parties?"

- Other teams from different disciplines/departments in your organization
- Domestic for-profit companies
- Domestic universities
- Domestic non-profit organizations, including large research institutes
- Overseas universities
- Other overseas organizations (for-profit companies and not-for-profit institutions)

Availability of funding

This factor was selected for inclusion in the Index as it was a recurring theme of importance through our expert interviews.

Data for this element was taken from our survey questions which asked "How would you rate the availability of the following types of funding in your country?":

- Direct government funding, for each stage of research
- Government tax incentives for R&D
- Private sector funding, for each stage of research

Also included in this element was a measure taken from existing publicly available data to capture the absolute amount of funding within a country, relative to that country's size. For our national results, we used total GERD for each country divided by that country's GDP.

CONSTRUCTING THE INDEX

For each of the above variables, an average of the answers for each country and industry was estimated. Where the answers to the questions were numerical (e.g. "what proportion of your research budget is spent with third-party research organisations?"), this was a simple average. Other questions had answers on a Likert scale, with answers such as "very much agree, partially agree, partially disagree, very much disagree". These were assigned values, such as 4 to "very much agree" down to 1 for "very much disagree". A numerical average of these values was then taken for each country and industry.

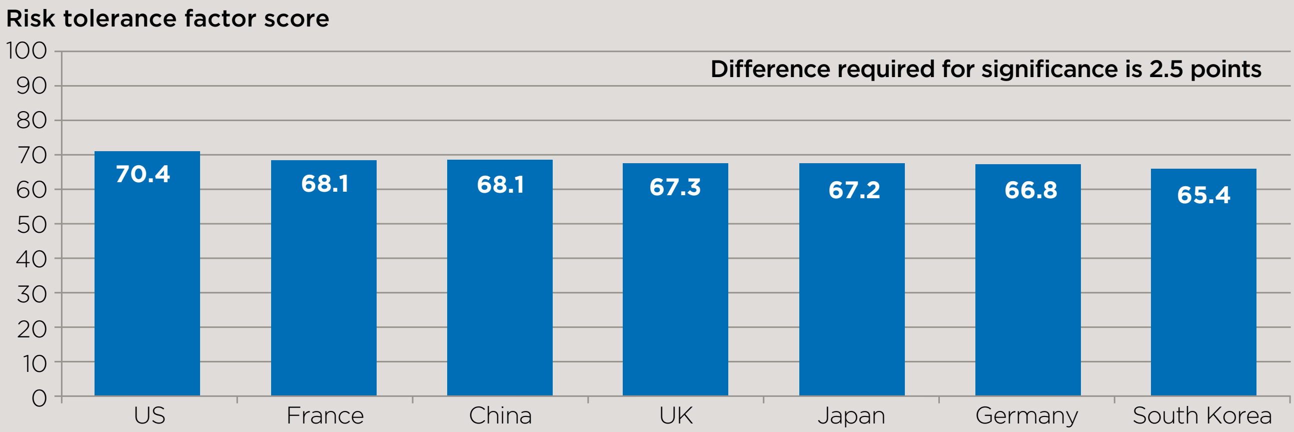
These averages were then compared to the theoretical maximum and minimum scores for each question—a technique known as calculating the "distance to the frontier", used for instance in the World Bank's Ease of Doing Business Index. The theoretical maximum for each question would be if every respondent gave the answer that demonstrated the most supportive environmental conditions for research, such as administrative burdens taking their time away from research "not at all" burdensome. The theoretical minimum is the reverse, if every respondent gave the answer that demonstrated the least supportive environmental conditions, such as administrative burdens taking their time away from research "completely".

This distance to the frontier is calculated for each question, and then all questions are averaged within each variable to give that variable's score. The average score across all six variables is then taken to give the overall Index score for each country and industry.

TESTING FOR SIGNIFICANCE

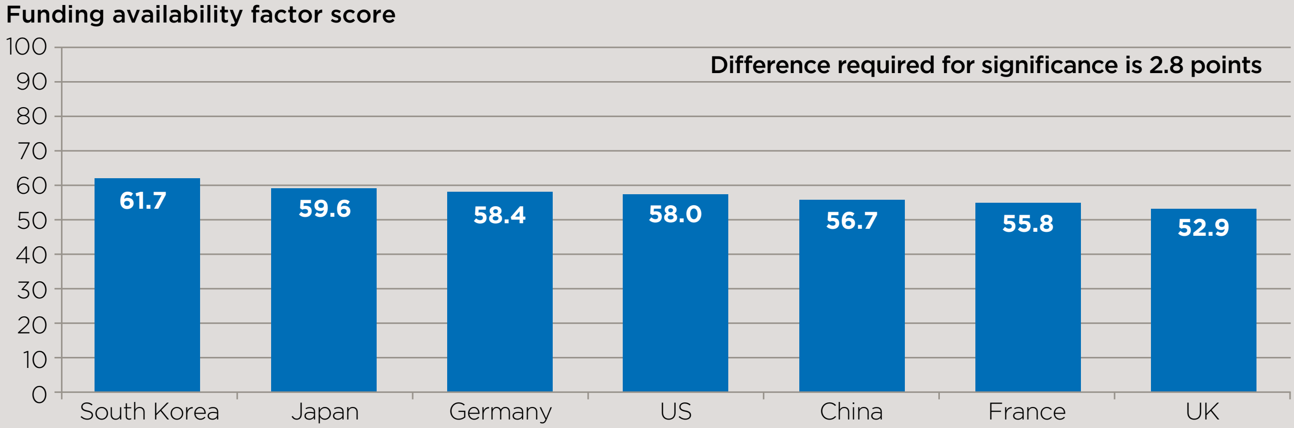
To test for statistically significant differences between country responses to the survey questions used to calculate the Pulse Check, we used a two-sample t-test. We also used a goal seeking method to determine the theoretical minimum difference in means required for statistical significance for each separate question. These theoretical minimum values were averaged across each question within a Pulse Check factor, and averaged across all six factors to give an illustrative value required for significance for the overall Pulse Check at the country level.
The differences required for each individual factor are given in the charts below.

Fig. 35: Risk tolerance Pulse Check factor scores by country



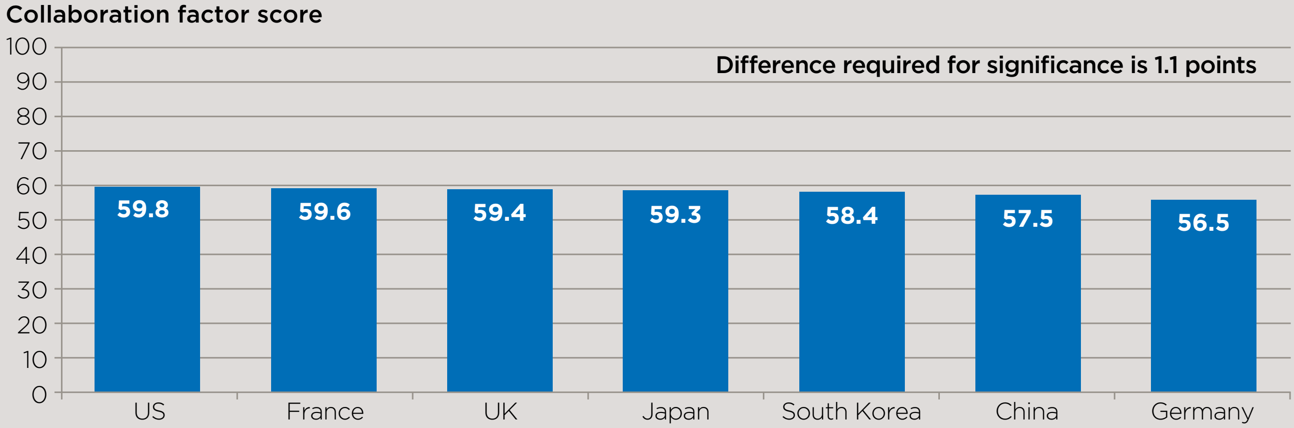
Source: Oxford Economics

Fig. 36: Funding availability Pulse Check factor scores by country



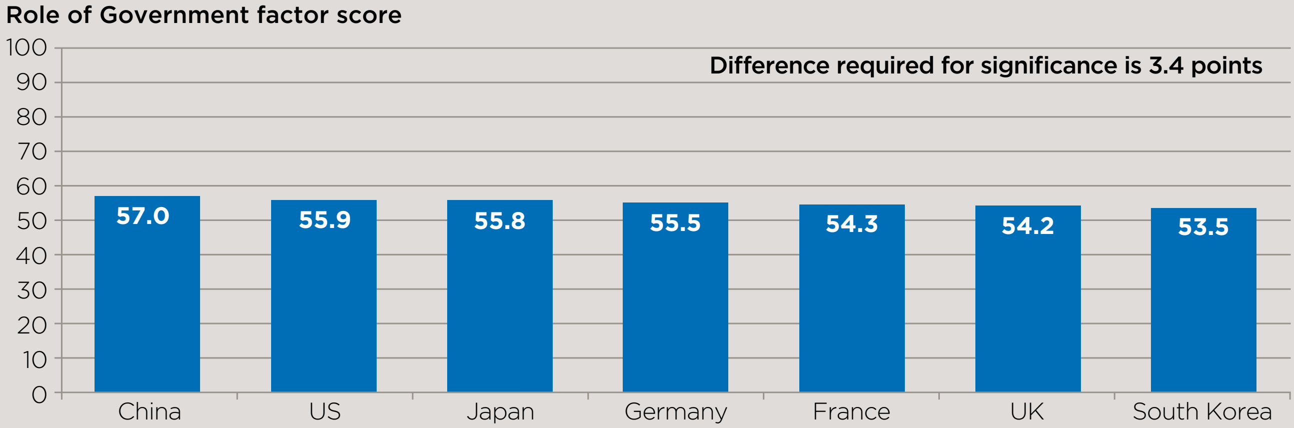
Source: Oxford Economics

Fig. 37: Collaboration Pulse Check factor scores by country



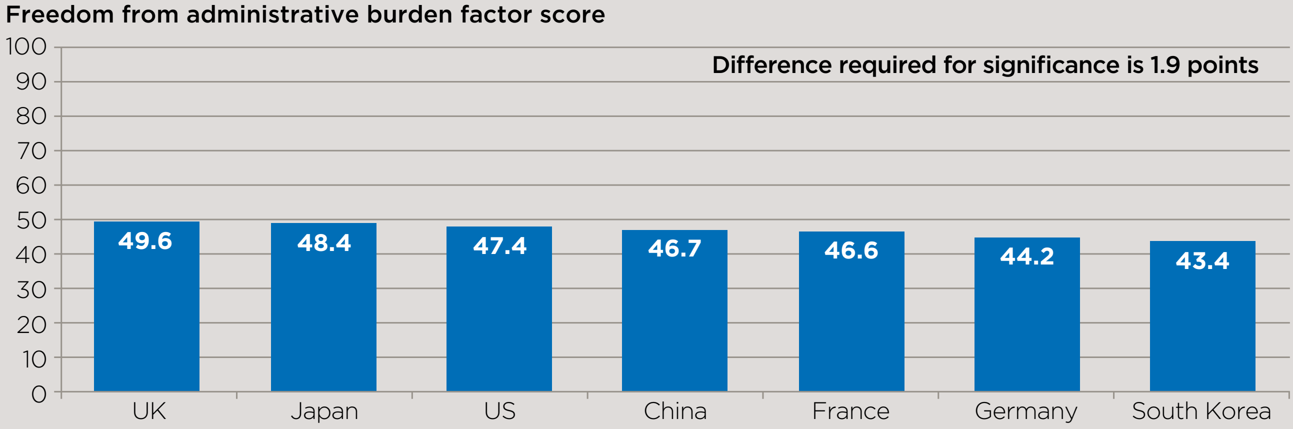
Source: Oxford Economics

Fig. 38: Role of Government Pulse Check factor scores by country



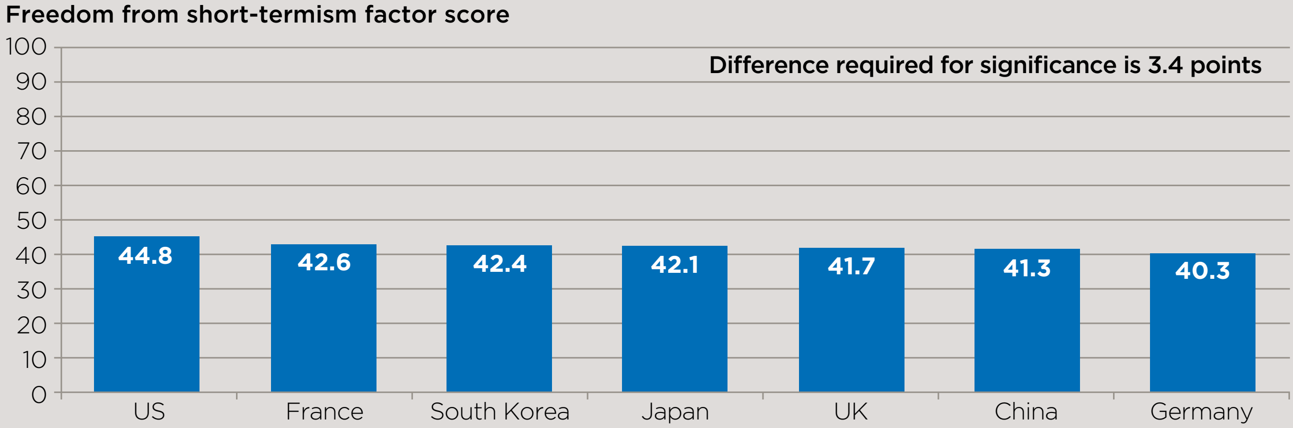
Source: Oxford Economics

Fig. 39: Freedom from Administrative Burden Pulse Check factor scores by country



Source: Oxford Economics

Fig. 40: Freedom from Short-termism Pulse Check factor scores by country



Source: Oxford Economics

APPENDIX 5: FULL BIBLIOGRAPHY

In this appendix we provide a full list of the papers considered as part of the literature review. This includes both those from which we drew evidence used in this report, and those that on review did not prove central to the themes we have discussed.

A Global Decline in Research Productivity? (Boeing and Hünermund, 2020)

How pursuing patents in Japan has evolved over the past decade (Clarivate, 2020)

Untapped opportunities for semiconductor companies (KPMG, 2020)

How to solve R&D productivity challenges: 10 innovators share their strategies (PatSnap, 2020)

From vision to decision (PwC, 2020)

How to spot dodgy academic journals (The Economist, 2020)

The Top 10 Artificial Intelligence Trends Everyone Should Be Watching in 2020 (Forbes, 2020)

Duplicate and salami publication: a prevalence study of journal policies (Ding et al., 2020)

R&D Outsourcing and the Decline in R&D Productivity (Knott, 2020)

US Research and Development Funding & Performance Fact Sheet (Congressional Research Service, 2020)

Technology Readiness Levels: NASA's contribution to Horizon 2020 (EIT Health, 2020)

More D! A more development-focused strategy for paving the way to impact (AIRTO, 2020)

Are ideas getting hard to find? (Bloom and Jones, 2019)

What do we mean by scientific productivity - and is it really falling? (Jones, 2019)

Is the rate of scientific progress slowing down? (Cowen and Southwood, 2019)

What's next for semiconductor profits and value creation? (McKinsey, 2019)

Ten years on - Measuring the return from pharmaceutical innovation (Deloitte, 2019)

Global aerospace patents: Technology, innovation, and competition strategy (ATL, 2019)

Spillovers: Revealing the broader economic benefits of aerospace R&D (Aerospace Technology Institute, 2019)

On the Decline of R&D Efficiency (Miyagawa and Ishikawa, 2019)

Who Becomes an Inventor in America? The Importance of Exposure to Innovation (Bell et al., 2019)

On the Decline of R&D Efficiency (Tsutomu & Takayuki, 2019)

Factors that influence scientific productivity from different countries: A causal approach through multiple regression using panel data (Lancho-Barrantes, ceballos and Cantu-Ortiz, 2019)

Innovation and invention, evidence from the quota acts (Doran and Yoon, 2019)

The Endless Frontier? The Recent Upsurge of R&D Productivity in Pharmaceuticals (Pammoli et al., 2019)

A Toolkit of Policies to Promote Innovation (Bloom et al, 2019)

Why Is Productivity Down When Innovation Is Way Up—And What Do We Do About It? (Chesbrough, 2019)

Pharmaceutical R&D global spending trends in 2019 (Singh, 2019)

Global Biopharma R&D Productivity and Growth Rankings (Scholefield and Thunecke, 2019)

Declining Efficiency of R&D in Pharma Corporations (Deep Knowledge Analytics, 2019)

How long-term university-industry collaboration shapes the academic productivity of research groups (Garcia, 2019)

Outsourced Pharma Services (Clearwater International Healthcare, 2019)

AI and the modern productivity paradox (Brynjolfsson, Rock and Syverson, 2018)

How do you define and measure research productivity? (Abramo and D'Angelo, 2018)

Have R&D spillovers changed? (Lucking, Bloom and Van Reenen, 2018)

Modelling science trustworthiness under publish or perish pressure (Grimes et al., 2018)

The STM Report An overview of scientific and scholarly publishing (Johnson et al., 2018)

Too much academic research is being published (Altbach and De Wit, 2018)

The digital economy, GDP and consumer welfare: theory and evidence (Brynjolfsson, 2018)

Productivity measurement in the digital age (Pells, 2018)

The dangers of overspecialization in academia (Big Think, 2018)

Unlocking R&D productivity - Measuring the return from pharmaceutical innovation (Deloitte, 2018)

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November 2021

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