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Corresponding Author:
Lin Zhang
linzhang1117@whu.edu.cn

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RESEARCH ARTICLE

Gender differences in the patterns and consequences of changing research directions in scientific careers

Lin Zhang[1,2,3], **Fan Qi**[1,2], **Gunnar Sivertsen**[4], **Liming Liang**[5], **and David Campbell**[6]

[1]Center for Science, Technology & Education Assessment (CSTEA), School of Information Management, Wuhan University, Wuhan, China
[2]Center for Studies of Information Resources, School of Information Management, Wuhan University, Wuhan, China
[3]Centre for R&D Monitoring (ECOOM) and Department MSI, Leuven, Belgium
[4]Nordic Institute for Studies in Innovation, Research and Education, Oslo, Norway
[5]Institute for Science, Technology, and Society, Henan Normal University, Xinxiang, China
[6]Science-Metrix, an Elsevier company, Montreal, Quebec, Canada

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ABSTRACT

Changes of research direction in scientific careers are related to the so-called "essential tension" between the exploration of new knowledge and the exploitation of established knowledge in research and innovation. Changes of research direction are thereby assumed to influence the evolution of science in general. Research has shown that such changes may also affect the success of individual scientists in their careers. However, the gender dimension of this aspect of career development is so far understudied. There is also a need for more dynamic indicators to record and interpret career developments in macro data. This study combines the gender perspective with the introduction of new indicators. We selected more than 29,000 scientists in Physics & Astronomy and studied them over six decades using a bibliographic data set from Scopus. We find that women are less likely to change research direction than their men counterparts, and that the research performance of women is less negatively affected by changing research direction. We discuss the policy implications of these findings as well as the methodological advancement related to the new indicators of career development.

1. INTRODUCTION

Shifts in research topics and direction during scientists' careers are shaping the general evolution of science (Foster, Rzhetsky, & Evans, 2015) and may also significantly influence research performance and career advancement at the individual level. Investigating new topics and fields and engaging in new directions is normal in research. By combining atypical knowledge, scientists may strategically make breakthroughs and pursue successful research careers, but this endeavor is also risky and associated with potential failures. Kuhn (1963) named this conflict the "essential tension" between tradition and innovation in scientific development. Scientists are faced with the choice between exploration and exploitation (March, 1991) in their scientific careers. Given the background of observed gender differences in research practices (Ceci, Williams, & Barnett, 2009), one may ask whether the patterns of changing research direction also differ by gender? If so, will this difference also lead to different research performance?

The strategies and patterns for shifting research directions have attracted considerable attention in philosophy of science (Polanyi, 1969), sociology of science (Bourdieu, 1975), innovation studies (March, 1991), and recently in quantitative science studies (Huang, Lu et al., 2022). In recent years, the increased availability of large scientific data sets has provided more opportunities to discern changes in scientists' research topics and directions and to measure the dynamics of their changes throughout their careers. Different kinds of bibliographic information have been used to for this purpose. Jia, Wang, and Szymanski (2017) utilized the Physics and Astronomy Classification Scheme (PACS) codes to denote the research topics and study how scientists choose and shift their research focus over time. Zeng, Shen et al. (2019) employed a cocitation network to generate research topics and discovered a narrow distribution of topics among scientists. Ma, Song et al. (2020) constructed a two-layer network model, incorporating scientists' collaboration and topic similarities, to analyze the association between the career stage switch and research topic change. Hellsten, Lambiotte et al. (2007) used an author's self-citation network, coauthorships, and keywords in self-citing articles to detect the field mobility of a scientist.

Some studies have focused on how exploration-exploitation strategies affect scientists' innovation and scientific performance as measured by bibliometric indicators. It has been documented that scientists who take the risk of switching research interests and pursue a diverse research agenda tend to produce highly innovative outcomes (Foster et al., 2015; Liu, Dehmamy et al., 2021) and have a long career in academia (Ma et al., 2020). However, when it comes to productivity, moving to new fields of research can be disadvantageous. Zeng et al. (2019) found that a high probability of switching research topics in early career is associated with low overall productivity. To diversify rather than specialize can negatively influence the bibliometric performance (publication and citations) of scientists because the "rewards" of diversification, a metaphorical term for its positive effects, do not balance the risk of failing to publish (Abramo, D'Angelo, & Di Costa, 2019; Foster et al., 2015).

However, the study of changes in research topics and directions has so far not included gender perspectives. Other aspects of gender differences in research practice (Zhang, Shang et al., 2022) and knowledge production have been explored. On the one hand, men and women have different distribution patterns across research topics. It has been shown that women are overrepresented in veterinary science and cell biology (Thelwall, Bailey et al., 2019) but are underrepresented in math-intensive fields (Ceci et al., 2009). Research on gender equality also features a dominance of female first authors (Shang, Sivertsen et al., 2022). Generally, women were also found to undertake more interdisciplinary research (Pinheiro, Durning, & Campbell, 2022). On the other hand, gender differences also exist in risk-taking. Prior studies suggest that men take more risks than women, regardless of context (Kelling, Zirkes, & Myerowitz, 1976), including in various aspects of their lives (Eckel & Grossman, 2008), in doing tests (Swineford, 1941), and in making hypothetical (Powell & Ansic, 1997) and investment choices (Barber & Odean, 2000). In academic contexts, the research agendas of women have been proved to be less risky but more collaborative (Santos, Horta, & Amâncio, 2021), which could lead to a lower propensity of changing research direction given its associated risk. Some studies also linked different practices with their research performance. Zhang, Sivertsen et al. (2021) found that differences in the greater scientific impact of men and the greater societal impact of women researchers could be attributed to gender differences in the aims of research projects. Work by Leahey (2006) suggests that women specialize less than men and thereby have lower productivity.

In the context of research strategy, the choice of topics and directions may also be different between genders (Fox, Whittington, & Linková, 2017) due to the interrelated factors, general values, and risk-taking preferences mentioned above. For instance, various interrelated factors are found to contribute to multifaceted gender differences in academia. Fox (2005) found that types of marriage and family composition (i.e., the presence or absence of children) have different influence on the publication productivity for women in academia. Keith, Layne et al. (2002) highlighted the importance of the organizational context to explain the gender differences in publication outcomes. Xie and Shauman (1998) held that gender differences in research productivity can be attributed to gender differences in personal characteristics, institutional positions, and marital status. Various concepts have been introduced in documenting or explaining gender differences in academia, such as the "productivity puzzle" (Cole & Zuckerman, 1984), denoting that women publish fewer scientific papers than men, the "Matilda effect" (Lincoln, Pincus et al., 2012), denoting a bias against acknowledging the achievements of women scientists whose work is attributed to their male colleagues, and the "devaluation theory" (Magnusson, 2009), denoting that women are culturally devalued in society. Recent studies in psycholinguistics and neurology also suggest that gender differences in "preferences" for certain fields or topics, as well as risky endeavors, can likely be attributed to social "norms" rather than to biology (Byrne, 2023). These norms would have shaped the "gendered" brain over centuries, notably through the use of gendered languages (Bigler & Leaper, 2015; Byrne, 2023; Lewis & Lupyan, 2020).

Whether the above gender differences in core research areas and topics are also accompanied by changes of research direction, and how they affect careers, has not been studied so far. On this background, a closer investigation of possible gender differences in the patterns and impacts of changing research directions is warranted. The patterns of research direction changes might be different and have different consequences for research performance. A gender perspective on this topic may also contribute to the understanding of more general gender differences in academia.

In this study, we first introduce a set of indicators to illustrate the patterns of changing research directions and make a comparison between men and women. Then, we establish a connection between changing direction and research performance to analyze whether shifts of directions lead to different consequences for men and women. We employ a Scopus data set comprising 29,194 scientists from the Physics & Astronomy field and their published articles to perform the analysis. The specific research questions of this study are as follows:

1. Are there gender differences in the patterns of changing research directions?
2. How does the trajectory of changing research directions evolve throughout scientific careers? Are there any gender differences in this trajectory?
3. How do changes of research direction influence scientists' research performance? Are there any gender differences in this influence?

The major field of Physics & Astronomy was selected for this study for the following reasons:

1. Gender issues in physics are a longstanding concern in academia (Eaton, Saunders et al., 2020; Madsen, McKagan, & Sayre, 2013; Strumia, 2021a). A controversial hypothesis that no significant gender differences exist in fundamental physics (Strumia, 2021a) immediately provoked intense debate and discussion (Andersen, Nielsen, & Schneider, 2021; Ball, Britton et al., 2021; Hossenfelder, 2021; Strumia, 2021b; Thelwall, 2021). Hence, more research is needed to further understand this issue in physics from new perspectives.

2. Given the considerable existing literature on researchers changing research directions and topics in physics (Battiston, Musciotto et al., 2019; Jia et al., 2017; Yu, Szymanski, & Jia, 2021; Zeng et al., 2019) with almost no discussion of the gender perspective in this context, this study seeks to fill this gap and contextualize our findings by engaging in meaningful discussions with the existing pioneer studies within the physics domain.
3. Physics encompasses a range of diversified yet well-differentiated subfields, providing an advantageous framework within which to explore research direction changes among scientists.

By connecting changing research directions and the gender of the scientists for the first time, this study contributes to a better understanding of gender differences in research direction changes and how they may impact the research performance of men and women in different ways.

The rest of this paper is organized as follows. In Section 2, we introduce our data set and the proposed quantitative indicators of changes in research directions. Relying on cross-sectional and time-series data, three indicators are proposed. We later show how they better capture dynamic aspects of careers compared to existing methods measuring research direction changes statically (Jia et al., 2017). Section 3 provides the quantitative analysis, while we discuss our results and their implications and conclude in Section 4.

2. METHODOLOGY

2.1. Data Set

The data used in this study is derived from Scopus and was provided by the International Center for the Study of Research (Elsevier). An article-level classification developed by Science-Metrix is adopted to uniquely assign research fields and subfields to articles. The Science-Metrix classification is hierarchical and categorizes articles into five domains, 20 fields, and 174 subfields[1]. In this classification, a scientific publication is attributed to only one domain, field, and subfield based on its title, abstract, keywords, author affiliation, and citations, using a deep neural network. This approach is effective even in cases where citation information is unavailable, thereby being complementary to citation-based classification approaches such as bibliographic coupling and direct citation-based classifications. In addition, it is proven to perform as well as the citation-based classification approaches but has more flexibility for further improvement (Rivest, Vignola-Gagné, & Archambault, 2021).

Our study chose the case of physics to investigate gender differences in changes of research direction. Using the Science-Metrix classification, we therefore selected all articles classified within the field of Physics & Astronomy. This field includes nine subfields: Acoustics, Applied Physics, Astronomy & Astrophysics, Chemical Physics, Fluids & Plasmas, General Physics, Mathematical Physics, Nuclear & Particle Physics, and Optics. The research directions of scientists in this study are defined using these nine categories. A change of research direction is defined as an observed change of subfield(s) in the time series of the first and corresponding-authored publications by a scientist (more details on the definition of research direction and changing research directions are available in Section 2.2). Scientists often collaborate across fields or subfields as coauthors without changing research direction. Hence, we only consider publications where a scientist contributed as first or corresponding author, assuming that these positions reflect that he or she played a *leading* role in selecting the primary research direction of the study. A potential

[1] https://www.science-metrix.com/classification/.

problem for this methodological choice is that high-energy physics may practice alphabetical ordering of authors (Fernandes & Cortez, 2020). However, only 1.25% of the articles in our data have authors in alphabetical order and should thereby have limited impact on our analysis.

To explore research direction changes, we use the subfields within Physics & Astronomy (according to the article level of thematic classification from Science-Metrix) in which the scientists publish to represent the research directions of scientists. The shifts from one publishing subfield to another (as defined by Science-Metrix) during scientific careers are referred to as changes of research directions[2]. The reasons for choosing "subfields" as the analysis level, instead of "major fields" or "research topics," are two-fold: Compared to higher levels of thematic classification (i.e., major fields), changes of subfield are more prevalent among scientists, making it more feasible to study the overall gender differences in academia; and "research topics" are usually defined by clustering methods, topic modeling, or word embeddings, the results of which may not be very consistent or reliable for comparison. In addition, publication changes of fine-grained "research topics" (e.g., within a given subfield) are more frequent among scientists and may not truly reflect changes of research direction. Here, we are studying changes in more long-term commitments that may demand new expertise.

We started in February 2023 by collecting from Scopus all 3,582,911 journal articles classified in the field of Physics & Astronomy and published in the period of 1960–2022. Each author ID in Scopus is identified as a scientist in our study. The author disambiguation of author ID is based on author name, affiliations, coauthors, subject areas, and publications. This method is verified as reliable for large-scale analyses at the individual level by several studies (Aman, 2018; Campbell & Struck, 2019; Kawashima & Tomizawa, 2015; Moed, Aisati, & Plume, 2013). Authors with original affiliations (i.e., the address in the first published article) in Asian countries were excluded due to the complexity of author name disambiguation and gender inference for Asians. To observe the changing trajectories of research directions along a relatively long and active research career, we limit our analysis to scientists who:

- authored at least one *leading* publication (first or corresponding author) every three years;
- published at least 10 *leading* publications in total;
- published *leading* publications for at least 20 years; and
- published in more than one subfield of Physics & Astronomy.

The records of scientists who publish beyond the major area of Physics & Astronomy are not included in this study because they exhibit a higher level of research direction shifts and are not comparable with the direction changes within physics. This study focuses on the physics community and aims to find out how men and women scientists with similar research backgrounds and paradigms differ in changing research directions. The data set includes 39,332 active scientists with sufficient lengths of scientific careers and with observed changes in research direction.

The authors' gender is inferred using a machine-learning-based classifier, Namsor. It estimates the possibilities of a binary classification of gender based on the authors' names and countries. We evaluate the results by the gender inference score derived from name and country information, as well as name-only inference scores. To ensure the reliability of gender inference, we included only those scientists whose scores (name and country based or name-only based) exceed a threshold of 0.85. Asian scientists are excluded due to the unsatisfactory

[2] In previous studies, this phenomenon is also named as changes in research interests.

performance of the gender inference algorithm in their case. Ultimately, we obtained 26,568 scientists with masculine-coded names and 2,626 with feminine-coded names using reliable gender inference, accounting for 74.22% of all the scientists meeting the criteria above.

2.2. Indicators and Measurements

To study scientists' changes of research direction, we have developed three indicators to measure the span of the changes, the scope of the changes, and the timing of first change. We name them *ChangeDegree, Broadness*, and *FirstChange* (Figure 1). Among them, *ChangeDegree* is calculated annually to reflect the dynamics of research direction shifts along the scientific career. *Broadness* measures the diversity of scientists' research directions over all the years from a static perspective. *FirstChange* accounts for the first time a change of research direction appears in a scientific career. We did not calculate the number of specialization changes in scientific careers, as it is demanding to distinguish scientists who change their research directions frequently from those who publish papers in limited subfields repeatedly. The time lag of publication can also affect the results, making them less interpretable and persuasive. By combining the dynamic and static view, these indicators provide a holistic understanding of how scientists' research directions evolve over time.

By composing topic vectors for papers, Jia et al. (2017) took advantage of cosine similarity between topic vectors to quantify changes of research interests. In this pioneering work, they compared the first and last *m* papers in a scientist's publication sequence to capture the change of research interests throughout a scientist's whole career as observed from a macro perspective. As a complement to this type of vector, we focus on the dynamics of research direction changes as they evolve throughout scientific careers, thereby capturing the development in more detail and focusing on larger step changes by running the analysis at the level of subfields instead of topics. Thus, we propose the new indicator, *ChangeDegree* (*S*), to compare the publications in a year with all the previous publications to quantify the degree to which a scientist changes his or her research directions annually and accumulatively. As explained above, a change of research direction is operationally defined based on the article-level classification of subfields in Physics & Astronomy from Science-Metrix, where each article is

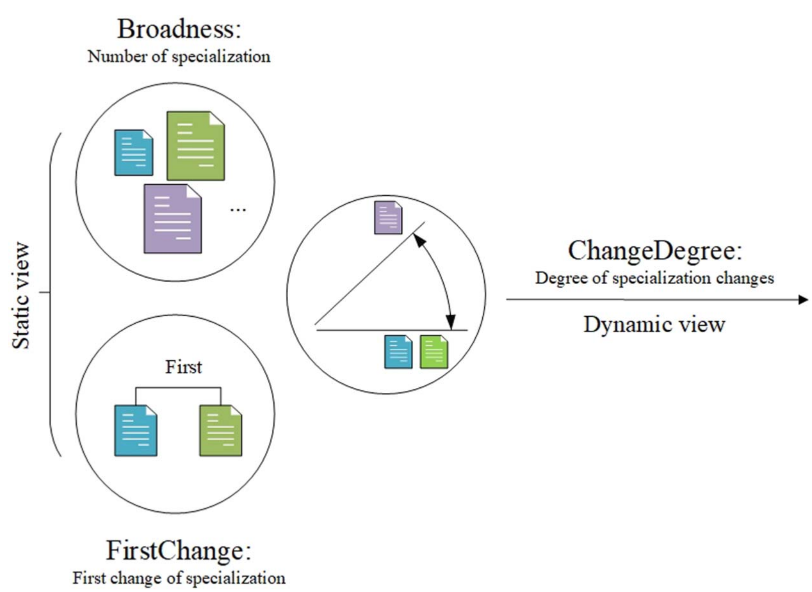

Figure 1. Indicators to quantify changes of research direction among scientists.

assigned a unique subfield label. Accordingly, the subfield within physics of a *leading* publication represents the research direction of a scientist at the time it is published. For a given set of articles that a scientist published in a year t, we generate a subfield vector $V_{y=t}$, the elements of which represent the occurrence of each subfield. Therefore, this vector captures not only the collection of subfields a scientist published in, but also the level of involvements in each of these subfields. We also calculate the accumulated subfield vector $V_{y=0}^{t-1}$ by taking advantage of papers published by scientists in the range from year 0 to year $t-1$ in our experiment (Figure 2) so that we can quantify the full scale of their past research experience. In this way, by comparing the vector of a focal year with the accumulative vector, we can accurately analyze to what degree a scientist has changed research directions (i.e., stepped into a completely new subfield or combination of subfields) or explore the past research interests (in the same proportions) again. Mathematically, we use the complementary cosine similarity S_t between the subfield vectors in the focal year t and all previous years (from year 0 to $t-1$) to quantify the annual change of research direction of a scientist as:

$$S_t = 1 - \cos\left(V_{y=0}^{t-1}, V_{y=t}\right)$$

S_t captures to what extent a scientist changed his or her research direction in a given year t, compared with his or her past research experience. $S_t = 0$ indicates that the two topic vectors $V_{y=0}^{t-1}$ and $V_{y=t}$ are identical, capturing the fact that the scientist studied the same set of subfields with the same level of involvement as before. $S_t = 1$ corresponds to a complete change in research direction, in which a scientist does not engage in any past subfields as appeared in previous years. In other words, a higher value of S_t indicates a greater difference in the combination of subfields studied in year t compared to the past, while a lower S_t suggests a replication of the prior research interests in year t or an attempt to balance new research directions with the past ones. To capture the differences of research directions in multiple dimensions, the complementary cosine similarity is more suitable for this study, compared to other methods (e.g., the Jaccard or Dice indexes). A recent study shows that cosine similarity-based embedding distance outperforms other forms of distance measures (Murray, Yoon et al., 2023). Jaccard or Dice indexes can only reflect the number of unique consistent elements between two samples, which can be biased for scientists who publish many papers in a subfield in 2 adjacent years. For instance, given scientist A, who published nine papers in general physics and one paper in applied physics before 2000, and one paper in general physics in 2001, and scientist B, who published one paper in general physics and one paper in applied physics before 2000, and one paper in general physics, the values of the Jaccard and Dice indexes for these two scientists will be the same but *ChangeDegree* is able to capture nuanced differences, including the past research directions, publishing in different subfields, and the number of papers in each subfield.

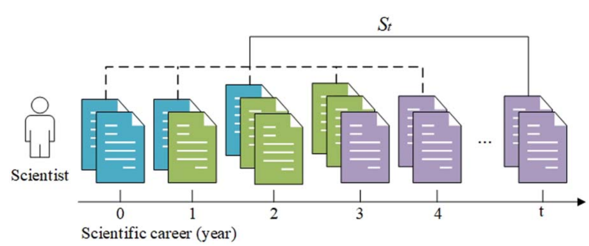

Figure 2. The framework to calculate *ChangeDegree* (S) of a focal scientist. The color of publications represents the subfield in which it is published. The axis represents the scientific career of the focal scientist at the year scale.

In addition, inspired by the variety indicator for analyzing diversity in science, technology, and society (Stirling, 2007; Zhang, Rousseau, & Glänzel, 2016), we propose *Broadness* to capture the number of subfields a scientist has contributed to:

$$Broadness = \sum subfield$$

A higher *Broadness* value indicates a wider range of subfields that a scientist has been involved in, reflecting a broader scope of research directions.

We also introduce *FirstChange* to determine the first time a scientist changed research directions throughout the scientific career. The reason why we focus on the first change is that this event marks the scientist's first adoption of an exploration strategy whose timing might impact the scientist's later success in its career (in terms of bibliometric performance). The scientist's academic age when the first change happens is also accounted for in calculating *FirstChange*, as it provides critical information on the career stage of the researcher at the time of adoption of an exploration strategy. *FirstChange* is thus calculated by subtracting the starting year of scientific career (in publishing) from the year when they first published beyond their initial research direction:

$$FirstChange = y_{1st\ change} - StartCareer$$

$y_{1st\ change}$ is the year when a scientist published articles in a new subfield for the first time. *StartCareer* is the year when a scientist published the first *leading* journal article.

Further, to measure the consequences of changing research directions on the research performance of scientists, we constructed two-way fixed effects panel data regression models. The descriptions of the variables are shown in Table 1. The indicators of productivity and citation impact of a scientist's publications are treated as the dependent variables while *ChangeDegree* (*S*) is the independent variable. Among those indicators, *ChangeDegree* (*S*) is the main explanatory variable because it is calculated as panel data, whereas *Broadness*[3] and *FirstChange* are treated as the control variables because they are cross-sectional data. Given that both productivity and citation impact are count data in our study (detailed calculations can be found in Table 1), we employed a Poisson regression model for data estimation. We introduce the year and the initial research direction[4] of scientists as fixed effects to control for the unobservable factors. In addition, several confounding (control) variables are identified that might directly or indirectly influence a scientist's research performance.

3. RESULTS

3.1. Gender Differences in the Patterns of Changing Research Directions

In this section, we first present how men and women scientists change research directions and then provide a detailed analysis of the characteristics of this activity.

The overall patterns of gender differences in changing research directions are shown in Figure 3a. In general, most of the scientists in physics (70.32%) have changed research direction by shifting the subfield in which they published over the course of their career, with 7.14% of them choosing to change their research direction beyond physics. Overall, the share of women among those who changed research direction within physics (8.98%) is lower than the overall share of women (10.14%). As such, women scientists have a slightly higher

[3] *Broadness* was omitted in the regression models because of the multicollinearity.

[4] The initial specialization of a scientist is defined as the subfield in which the first leading publication was published.

Table 1. List of variables for regression models

Variable	Description
Dependent variables	
Productivity	The number of articles each scientist published. This is counted by first-authored and corresponding-authored articles as the *Leading productivity*, while *Total productivity* is counted for all articles independently of author role. These variants are applied in different regression models.
CitationImpact	We use the number of articles belonging to the 10% most cited articles of all the articles in our data set to denote the citation impact at the individual level*. Citation impact per article is measured by the field-weighted citation impact (FWCI)** within various citation windows (i.e., up to now, four, and 5 years of time window). We run three alternative models for different citation windows. The *CitationImpact* counted on the basis of citations to first-authored and corresponding-authored articles is named as the *Leading CitationImpact*, while *Total CitationImpact* is counted on the basis of all articles of a scientist. These variants are applied in different regression models.
Independent variable	
ChangeDegree (*S*)	The extent to which a scientist changed research directions in each year.
Control variables	
FirstChange	The year of scientific career when a scientist changed research direction for the first time.
StartCareer	The year when a scientist published their first article.
LengthCareer	The time span from the year of the first article to the year of the last article published by the focal scientist.
Gender	The gender of a scientist inferred by Namsor. This equals 1 for scientists with feminine-coded names, otherwise 0.
TeamSize	The median number of coauthors of each scientist.
InterCollaboration	The share of articles with coauthors from different countries.

* This indicator is adopted from the percentile approach to normalized indicators proposed by Hicks, Wouters et al. (2015).

** Field-weighted Citation impact (FWCI) is a ratio between the number of citations a paper (or set of papers) has received, and the number of citations it may expect to receive, based upon the average number of citations per paper in the same subject category, article type, and publication year. (https://service.elsevier.com/app/answers/detail/a_id/14894/kw/FWCI/supporthub/scopus/).

tendency than men scientists to stay within their original research direction during their career. However, the share of women scientists who made a change of research direction beyond the field of physics (10.17%) is slightly higher than the overall share of scientists who left the field. It is also higher than the share of women among those who changed research directions within physics. This might indicate that women who seek to change their research direction find more favorable opportunities or face fewer barriers outside the traditional boundaries of physics. To observe possible trends over generations, we divided our data set into six groups according to the starting year of their scientific careers. Figure 3b shows that the number and share of scientists with a change of research direction has been rapidly increasing over time (except for the last decade, with an incomplete sample). However, there has been a widening gender gap in this increase. The tendency to change research directions among women did not increase at the same rate as the representation of women in physics.

We further present the characteristics of research direction changes with two static indicators, including in which stage of a scientific career a scientist starts to change their research direction and the broadness of the changes of research directions. As seen in Figure 4a, the

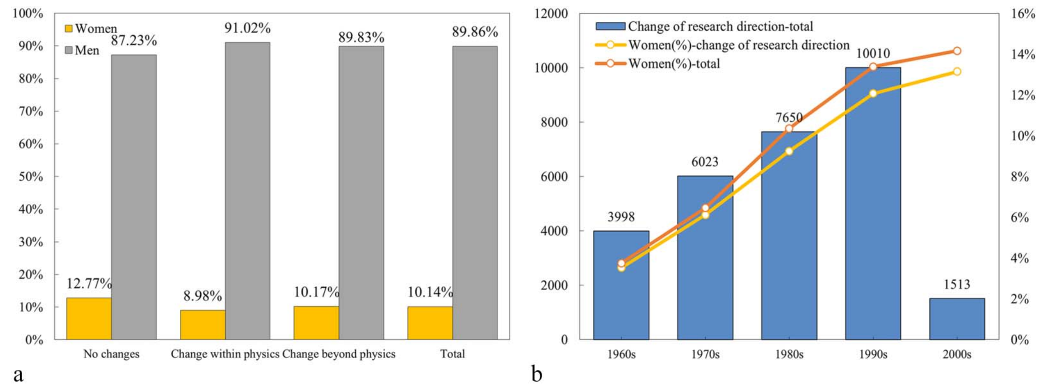

Figure 3. The gender differences in scientists who change research directions. a. From left to right: each pair of bars represents the distribution of scientists by gender for those who stick to a constant research direction, those who change research direction within the field of physics, those who change research direction beyond the field of physics, and the full sample of scientists in physics. b. Each bar represents the number of scientists who changed research direction from the 1960s to 2000s. The generation groups of scientists depend on the start year of their scientific career. The shares of women scientists who change research direction in each generation are plotted with the light-colored line. The share of women in the full sample (the dark-colored line) is plotted as the baseline.

mean value of the first research direction shift takes place within the first decade of a scientific career. The change happened earlier in the most recent generations. The most recent generation (the 2000s) made their first change in the sixth year on average. The increasing tendency to change early might be associated with increasing interdisciplinarity and more efficient scholarly communication. We also see from Figure 4a that men tend to change research direction earlier than women do, but this gap narrowed over time and disappeared after the 1990s. Although the confidence interval for men and women scientists overlaps for the breadth of physics subfields they explore during their career, the broadness calculated for men is very slightly, yet systematically, larger than for women across generations (Figure 4b). Generally, we find that most scientists in physics contribute to two to three subfields throughout their careers, which is consistent with earlier findings (Battiston et al., 2019). The earlier generations contributed to a wider range than the most recent generations. This is partly due to the higher degree of completeness of the careers of the scientists from earlier generations.

Our main finding is that men change research direction earlier and more often than women, but the differences in the timing of the first change have been narrowing through

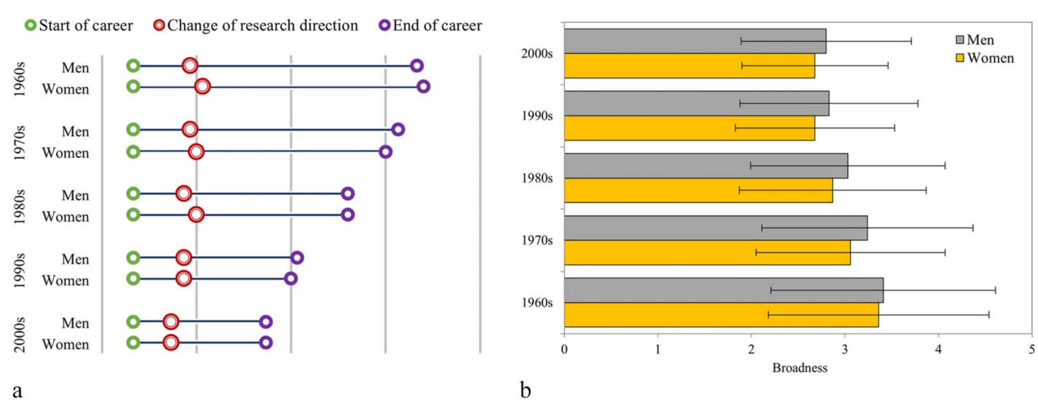

Figure 4. First time of changing research direction and broadness of research directions. a. Each line denotes the average scientific career of scientists in our sample. Three nodes are highlighted: the start (green), end (red), and *FirstChange* (blue) of scientific careers. b. The mean value of the *Broadness* of scientists' research directions in our sample. Error bars indicate the standard deviation (SD) of each sample.

generations. Moreover, the gap in the extent to which research directions change has increased in more recent generations as women trail further behind men.

3.2. Time-Series Analysis of Changing Research Directions in Careers and the Gender Differences

To investigate the dynamics of changes in research directions throughout careers, we calculated the median *ChangeDegree* (S) of a group of scientists for each year to reflect their overall level of research direction changes. We use the median value here instead of the mean value because the distribution of *ChangeDegree* (S) is skewed and the mean value can be affected by the extreme values. Used in a temporal perspective, this indicator reflects how changes of research direction have evolved over time in a career.

Based on the median value of *ChangeDegree* (S) of each group of scientists, we find that the evolution of the degree of change follows a similar pattern within the careers of all generations. The pattern is characterized by three phases. The median *ChangeDegree* (S) remains zero in the first few years, then increases significantly and reaches a peak in the following few years, and then, in the third phase, declines and maintains a relatively low value. A possible interpretation is that the scientists tend to concentrate on one or two research directions in the early phase of their scientific career. Then, they have the interest and opportunity to explore new topics and directions in the middle term of scientific career. In the later phase, they tend to make slight explorations into other subfields based on their existing research agenda. Scientists may apply a portfolio management of their research agenda (i.e., being more radical in the prime of their working life while more carefully distinguishing between primary and secondary interests in their later career).

The peak value of the median *ChangeDegree* (S) declines with the generations, indicating that recent generations tend to adopt *milder strategies* when changing research directions and that fewer scientists make great changes. This is understandable because the present modes of specialized knowledge production make it more demanding to innovate and make frequent changes in research directions with the growing burden of knowledge nowadays (Jones, 2009). With increased research directions, scientists are joining more collaborations to embrace the demand for interdisciplinarity. Current assessment criteria may also lead to risk-avoiding research strategies. Combined with the above findings in Figure 4a, it seems that younger generations start to change research direction earlier but to a lesser extent.

Regarding gender differences in the patterns of changing research directions, we performed bootstrapped analysis to reduce the impact of unbalanced sample and to obtain more accurate results. In Figure 5, the shades of each line indicate the variability and uncertainty in the *ChangeDegree* estimates. In the early stages of their scientific careers, women scientists typically exhibit greater changes in research direction compared to their men counterparts. However, this difference diminishes as their careers progress. In the 1960s, 1980s, and 1990s, women scientists even show fewer changes in the late stage. We also find that the peak value of *ChangeDegree* becomes less pronounced with generations. Men scientists show a distinct peak value in the early stage only in 1960s, while women scientists show a lower peak value after 1970s. Overall, the value of *ChangeDegree* and the overlap in confidence intervals between genders suggest that gender differences are not significant. In certain periods and stages of career (i.e., in late stage of career or the 2000s), the observed values of *ChangeDegree* are large and fluctuate due to the small size of sample in those groups.

For a robustness check of *ChangeDegree* (S), we introduced a variant *ChangeDegree* (S_5) with a moving 5-year time window. Specifically, for the publication sequence of each scientist, we compare the topic vector of the focal year with that composed by publications in the prior

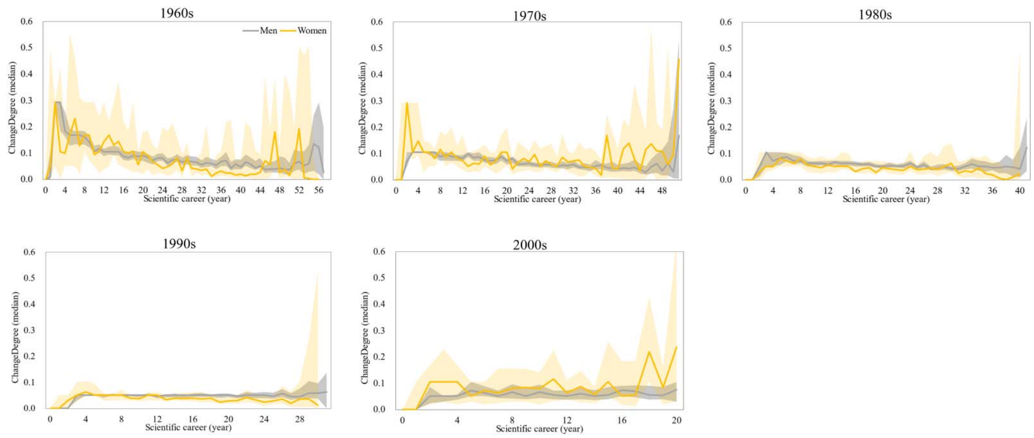

Figure 5. Gender differences in the evolution of the *ChangeDegree* (S) with 95% Bootstrap Confidence Intervals in scientists' careers. Median value of *ChangeDegree* in each year through the scientific career is calculated. Groups in different genders and generations are presented. The shaded areas around each line represent the 95% bootstrap confidence intervals, calculated using 1,000 bootstrap resamples.

five years. The moving time window is set to control for the magnitudes of publication counts of the focal and previous vector and to make them more comparable. Overall, the evolution of S_5 shows similar trends as that of S but with smaller values in the late stage of career. The gender differences in Figure 6 also agree with those in Figure 5. We find that the proposed indicator *ChangeDegree* can reflect the extent of changing research directions effectively. We also ran the bootstrapped analysis of S and S_5 with different sizes of resamples and again obtained similar results (Figures S1 and S2 in the Supplementary material), which confirms the robustness of gender differences in the *ChangeDegree* indicator.

3.3. Regression Analysis on the Relation Between Changes of Direction, Research Performance, and Gender

To test the exact effects of the degree of changing specialization research directions, we run regression models to account for other potential confounding factors. In particular, according to our research questions, we need to determine whether the effects are moderated by gender.

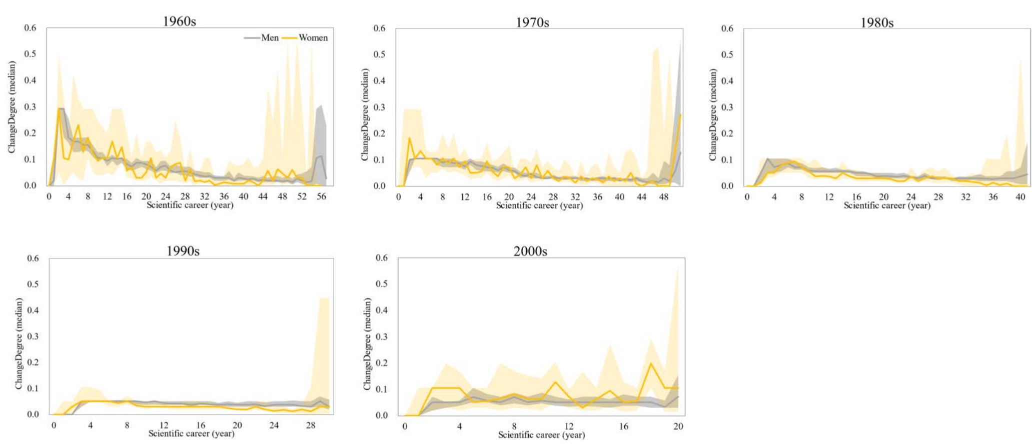

Figure 6. Gender differences in the evolution of the *ChangeDegree* (S_5) calculated with a moving 5-year time window and 95% Bootstrap Confidence Intervals in scientists' careers. Median value of *ChangeDegree* in each year through the scientific career is calculated. Groups in different genders and generations are presented. The shaded areas around each line represent the 95% bootstrap confidence intervals, calculated using 1,000 bootstrap resamples.

The regression analysis in this section is implemented through the "fixest" (Bergé, 2018) package of the R programming language.

In Table 2, we report the effect of *ChangeDegree* (*S*) on scientists' productivity, and only *leading publications* (first or correspondence-authored) are included. We start with the simplest model with only the main explanatory variable, and then add the control variables, fixed effects of the scientists' initial subfield, and fixed effects of year successively. In this process, the pseudo R^2 of our model increases, suggesting that its explanatory power is strengthened. The variable *ChangeDegree* (*S*) enters negatively and significantly in Table 2, columns (1)–(5), indicating that the degree to which a scientist changed his or her research directions has a negative

Table 2. Estimated relationships between the degree of changing research direction and scientists' productivity in publishing leading publications

Dependent variable: *Leading productivity*	(1)	(2)	(3)	(4)	(5)	(6)
ChangeDegree (*S*)	−0.3549***	−0.3576***	−0.3505***	−0.3573***	−0.3504***	−0.3552***
	(0.004)	(0.0041)	(0.0171)	(0.0664)	(0.0192)	(0.0197)
FirstChange		−0.0297***	−0.0345***	−0.0316***	−0.0362***	−0.0362***
		(0.0012)	(0.0052)	(0.004)	(0.0063)	(0.0063)
StartCareer		0.0079***	0.0083***	0.0045***	0.0048***	0.0048***
		(0.0002)	(0.0004)	(0.0006)	(0.0012)	(0.0012)
LengthCareer		0.0062***	0.006***	0.0049***	0.0047***	0.0047***
		(0.0002)	(0.0006)	(0.0004)	(0.0006)	(0.0006)
Gender		−0.04334***	−0.0433***	−0.0437***	−0.0443***	−0.0555***
		(0.0045)	(0.0042)	(0.0042)	(0.0046)	(0.0038)
TeamSize		0.0055**	0.0036	0.0071	0.005	0.005
		(0.002)	(0.0068)	(0.0039)	(0.0071)	(0.0071)
InterCollaboration		−0.5386***	−0.5379***	−0.5477***	−0.5496***	−0.5496***
		(0.0082)	(0.0238)	(0.0199)	(0.0293)	(0.0294)
*ChangeDegree***Gender*						0.061***
						(0.0063)
Year fixed effects	NO	NO	NO	YES	YES	YES
Field fixed effects	NO	NO	YES	NO	YES	YES
Observations	411,142	411,142	411,142	411,142	411,142	411,142
Pseudo R^2	0.0066	0.012	0.0126	0.0137	0.0151	0.0151

Note. Robust standard errors in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

effect on the production of leading publications. By controlling other covariates and fixed effects in the model, the coefficient remains stable and significant, thus proving the robustness of the results to some extent. Furthermore, to test whether the effects of changing research directions vary by gender, we added the gender of the scientists as the interaction term. In Table 2, column (6), the coefficient for the variable *ChangeDegree* (*S*) is negative, while for the interaction of *ChangeDegree***Gender* it is positive, suggesting that the variable *Gender* (women) weakens the effect of variable *ChangeDegree* (*S*). We thereby observe that the negative effect of the degree of changing research direction is weaker for women than for men.

We extend the results above by comparing the effect of *ChangeDegree* (*S*) on *leading productivity* with that on the *total productivity* (all publications, independently of author role) in Table 3. The model specification 6 as introduced in Table 2 is applied. Consistent with the

Table 3. Estimated effects of the degree of changing research directions on scientists' productivity

Variables	(1) Leading *Productivity*	(2) Total *Productivity*
ChangeDegree (S)	−0.3552***	−0.2419***
	(0.0197)	(0.0122)
FirstChange	−0.0362***	−0.0462***
	(0.0063)	(0.0075)
StartCareer	0.0048***	−0.0066***
	(0.0012)	(0.0019)
LengthCareer	0.0047***	0.0071***
	(0.0006)	(0.0013)
Gender	−0.0555***	−0.1198***
	(0.0038)	(0.0087)
TeamSize	0.005	0.285***
	(0.0071)	(0.0234)
InterCollaboration	−0.5496***	−0.3812***
	(0.0294)	(0.0427)
*ChangeDegree***Gender*	0.061***	0.0612***
	(0.0063)	(0.0156)
Year fixed effects	YES	YES
Field fixed effects	YES	YES
Observations	411,142	411,142
Pseudo R^2	0.0151	0.0852

Note. Robust standard errors in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

negative effect on the number of leading articles, the variable *ChangeDegree* (*S*) exhibits a negative effect on the total number of articles. That is to say, a large extent of changing research directions may result in a decrease of all the articles of scientists. The variable *Gender* is introduced as the interaction term as well. We find that the coefficients for the variable *ChangeDegree* (*S*) is negative, while for the interaction *ChangeDegree***Gender*, it is positive in Table 3, column (2), indicating a weaker effect for women scientists.

We now turn to the second bibliometric indicator of research performance as input for the dependent variable, the number of top 10% *leading publications*: first- or correspondence-authored publications belonging to the 10% most cited articles as measured by field-normalized citations, FWCI (Table 1). Table 4 shows the results of the regression analysis.

Table 4. Estimated relationships between the degree of changing research directions and the citation impact of leading publications measured by FWCI with no citation windows

Dependent variable: *Leading publications' CitationImpact*	(1)	(2)	(4)	(3)	(5)	(6)
ChangeDegree	−0.277***	−0.3221***	−0.3148***	−0.3045***	−0.2969***	−0.3029***
	(0.0109)	(0.0112)	(0.0164)	(0.0454)	(0.0483)	(0.0483)
FirstChange		−0.0711***	−0.0606***	−0.0801***	−0.0698***	−0.0698***
		(0.0112)	(0.0058)	(0.0174)	(0.0162)	(0.0162)
StartCareer		−0.0711***	0.0148***	0.0002	0.0144***	0.0144***
		(0.0034)	(0.001)	(0.0028)	(0.0017)	(0.0017)
LengthCareer		0.0012*	0.0113***	0.0059*	0.0105***	0.0105***
		(0.0006)	(0.0016)	(0.0027)	(0.0027)	(0.0027)
Gender		−0.1905***	−0.1848***	−0.1984***	−0.1906***	−0.2072***
		(0.0131)	(0.0104)	(0.0328)	(0.0326)	(0.0357)
TeamSize		0.0049	−0.0032	0.0126	0.0034	0.0034
		(0.0055)	(0.0105)	(0.0342)	(0.0342)	(0.0342)
InterCollaboration		−0.0176	−0.0199	0.0071	0.0293	0.0293
		(0.0229)	(0.0248)	(0.07)	(0.0699)	(0.07)
*ChangeDegree***Gender*						0.0869***
						(0.0192)
Year fixed effects	NO	NO	YES	NO	YES	YES
Field fixed effects	NO	NO	NO	YES	YES	YES
Observations	411,110	411,110	411,110	411,110	411,110	411,110
Pseudo R^2	0.0014	0.0036	0.0104	0.0046	0.014	0.014

Note. Robust standard errors in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

The coefficients for the variable *ChangeDegree* (*S*) are all negative and of similar scale for Table 4, columns (1)–(5). We find that the degree to which a scientist changes his or her research direction is negatively associated with the citation impact of leading publications, that is, scientists with a greater extent of change of research direction will result in a lower citation impact. By introducing the interaction term *ChangeDegree***Gender*, the coefficient is significantly positive, which is opposite to the coefficient for the variable *ChangeDegree* (*S*), indicating that the negative effect of *ChangeDegree* (*S*) on citation impact is weaker for women scientists.

To further investigate the effects of *ChangeDegree* (*S*) on scientists' citation impact, we compare in Table 5 the effect on highly cited leading publications versus the effect on highly

Table 5. Estimated effects of the degree of changing research directions on the citation impact of scientists

	Leading publications' *CitationImpact*			Total publications' *CitationImpact*		
Variables	(1) No window	(2) 5 years	(3) 4 years	(4) No window	(5) 5 years	(6) 4 years
ChangeDegree (S)	−0.3029***	−0.2959***	−0.2962***	−0.2197***	−0.2103***	−0.2071***
	(0.0483)	(0.0327)	(0.0326)	(0.0316)	(0.021)	(0.0222)
FirstChange	−0.0698***	−0.0885***	−0.0912***	−0.0822***	−0.0924***	−0.0935***
	(0.0162)	(0.0139)	(0.014)	(0.0166)	(0.0151)	(0.0154)
StartCareer	0.0144***	0.0086***	0.0085***	0.0002	−0.005	−0.0053
	(0.0017)	(0.0018)	(0.0017)	(0.0029)	(0.0028)	(0.0028)
LengthCareer	0.0105***	0.005	0.0045	0.0119***	0.008*	0.0076*
	(0.0027)	(0.0027)	(0.0027)	(0.0032)	(0.0032)	(0.0031)
Gender	−0.2072***	−0.1841***	−0.1855***	−0.2483***	−0.2326***	−0.229***
	(0.0357)	(0.0441)	(0.0383)	(0.0462)	(0.0533)	(0.0523)
TeamSize	0.0034	0.075	0.0793	0.3850***	0.4202***	0.4289***
	(0.0342)	(0.0431)	(0.0428)	(0.0249)	(0.0244)	(0.025)
InterCollaboration	0.0293	−0.0392	−0.0699	−0.1776	−0.1901	−0.2229*
	(0.07)	(0.0707)	(0.0682)	(0.1047)	(0.0977)	(0.1031)
*ChangeDegree*Gender*	0.0869***	0.0864	0.0722	0.1155***	0.1184**	0.1072**
	(0.0192)	(0.0522)	(0.043)	(0.0103)	(0.0449)	(0.0394)
Year fixed effects	YES	YES	YES	YES	YES	YES
Field fixed effects	YES	YES	YES	YES	YES	YES
Observations	411,110	411,142	411,142	411,110	411,142	411,142
Pseudo R^2	0.014	0.0238	0.0251	0.0627	0.0734	0.0771

Note. Robust standard errors in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

cited total publications. We use four and 5-year time windows, as well as no time window, for citations to test the breadth and time-sensitive effect of *ChangeDegree* (*S*). We observe that the degree to which a scientist changes research direction has negative effects on the citation impact of both the leading and the total publications. Regarding the gender differences of these effects, we find that the coefficients for the variable *ChangeDegree* (*S*) and the interaction *ChangeDegree***Gender* are all opposite in signs in Table 5, columns (4)–(6), suggesting that the negative effects on the citation impact of total publications may be minor for women scientists.

Because citation counts accumulate over time, the effects of *ChangeDegree* (*S*) on citation impact can be different in the short and long run. In Table 5, columns (1)–(3), the negative effects of *ChangeDegree* (*S*) on the citation impact of leading publications first decreases and then increases with the time window for citations. Similarly, the negative effects of *ChangeDegree* (*S*) on the citation impact of total publications increases with the time window for citations. The effects of the degree to which a scientist changes research directions are most pronounced for the long-term citation impact of leading articles and all the articles. These

Table 6. Results of regression analysis grouped by gender

	Productivity		*CitationImpact*	
Variables	(1) Men	(2) Women	(3) Men	(4) Women
ChangeDegree (S)	−0.356***	−0.2863***	−0.3059***	−0.1632***
	(0.0063)	(0.0109)	(0.015)	(0.0427)
FirstChange	−0.0392***	−0.0024	−0.0745***	−0.0064
	(0.0025)	(0.003)	(0.0046)	(0.0141)
StartCareer	0.0052***	−0.0003	0.0151***	0.0043
	(0.0004)	(0.0008)	(0.0007)	(0.0026)
LengthCareer	0.0049***	0.0022**	0.0108***	0.0072**
	(0.0003)	(0.0007)	(0.0009)	(0.0025)
TeamSize	0.0043	0.0166*	0.0015	0.0437*
	(0.0035)	(0.0066)	(0.0087)	(0.0196)
InterCollaboration	−0.5595***	−0.4468***	0.0042	0.3435***
	(0.0131)	(0.0211)	(0.0273)	(0.0791)
Year fixed effects	YES	YES	YES	YES
Field fixed effects	YES	YES	YES	YES
Observations	377,160	33,982	377,128	33,724
Pseudo R^2	0.0154	0.0141	0.0139	0.0203

Note. Robust standard errors in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

findings suggest different career strategies may be linked to different outcomes on key evaluation dimensions of researchers, indicating that evaluation approaches should be tailored to different career types.

For a robustness check of the moderating effect of gender, we divided our sample into groups of men and women scientists, and then performed the grouped regression models. We included all the control variables and fixed effects consistently with the above models. The results in Table 6 agree with the results of models using the interaction term (Table 4). A similar gender pattern is found for the effects on the productivity and citation impact of leading publications. The effect of the *ChangeDegree* (*S*) in the sample of men is also stronger than in the sample of women. Thus, the results are stable and robust.

4. CONCLUSIONS

4.1. Summary

This paper investigates gender differences in the patterns and consequences of changing research directions based on quantitative evidence from physics. A research direction is operationally defined as the subfield category of the scientist's publication at the time of publishing. We developed a set of three indicators based on cross-sectional and time series data to illustrate the static and dynamic characteristics of scientists' changes of research directions during their careers. The indicators and data were applied to panel data regression models to analyze the relationship between research performance and direction changes. Contributing methodologically to scientific career studies in general, the main indicator introduced in our study is the *ChangeDegree* (*S*), which allows for a more dynamic analysis by collecting information from different career phases.

Our findings show that gender differences exist in the choices and consequences of research direction changes in scientific careers. Firstly, women are less apt to change research direction than their men counterparts. They change research direction less often, and later in their career, than men. However, these gender differences have been narrowing over time through the generations. Regarding the degree of changing research direction, we found no significant differences between women and men scientists in general. Women scientists exhibit greater change of research direction in the early stage but less change in the late stage of their careers in comparison with men counterparts. Secondly, the negative correlations between research direction change degree and research performance (i.e., productivity and citation impact as measured for scientists' first and corresponding articles) is weaker for women than men.

In addition to the gender perspective, this study also investigates the relationships between research direction changes and research performance. We found that the degree of changing research direction is negatively associated with the productivity and citation impact of scientists' first and corresponding-authored articles and overall research performance. We also introduce the citation window of articles to analyze the time-varying effects of research direction changes on citation impact. Our findings show that the negative associations between the degree of research direction changes and scientists' productivity and citation impact slightly strengthen over time.

4.2. Discussion

Our study confirms some observations in previous studies, as referred to below, but also provides new findings. We found that the dynamic patterns of scientists' change of research directions evolve in three phases, as shown in Figure 5. A study conducted on condensed matter physicists supports this observation, revealing that scientists typically focus on just one narrow research theme during PhD training. Later, scientists usually broaden their research themes during the postdoctoral phase (Horlings & Gurney, 2013). A boost in diversification of research topics is likely to appear as scientists achieve tenure (Franzoni & Rossi-Lamastra, 2017). Similar findings are also reported by Zeng et al. (2019). Moreover, by leveraging the leading publications to represent the research directions of scientists, our study also indicates that scientists' major focus in the late phase of their careers is less changed than that in the early phases. This decreasing trend of *ChangeDegree* as measured with leading publications is more significant than as measured with all the publications (Zeng et al., 2019). This is reasonable because senior scientists tend to collaborate more but publish leading papers with fewer changes of major research focus in the later phases of scientific careers.

The connection between change of research direction and research performance has also received significant attention, although the conclusions from previous studies vary considerably. Early theories, such as that of Kuhn (1963), proposed that scientists might be unproductive for long periods if they follow a risky innovative strategy and change research direction. However, once they succeed with this strategy, they can produce novel knowledge and outputs. Similar conclusions have also been drawn in previous literature (Abramo et al., 2019; Siciliano, Welch, & Feeney, 2018; Zeng et al., 2019). Conversely, some studies also found that scientists who take the risk of changing research direction tend to produce publications with higher citation impact (Azoulay, Graff Zivin, & Manso, 2011; Chakraborty, Tammana et al., 2015; Yu et al., 2021). As shown in this study, the effects of changing research direction on a scientist's research performance are negative if leadership roles in publications, gender, and career stages are taken into account.

Our results demonstrate that women have a lower tendency to change their research direction and they will experience fewer negative effects when entering a new subfield. The reasons behind this are complex. It is proved that women's or feminine attributes are correlated with risk averse behavior (Meier-Pesti & Penz, 2008), which might be rooted in the societal and structural norms for being women. These psychological factors may contribute to women scientists' low intentions on average to take risk and change their research direction. In addition, regarding the low representation of women in physics, they are faced with more difficulties in creating networks and opportunities, being the minority in the community, which also may partly explain women's low intention of changing research direction. This may increase if marital and parental duties take up time from research. Taking so-called survivor bias into consideration, women who leave academia or migrate to another field are not observable in our sample, which may partly explain the low share of women changing research direction. Different consequences of changing research direction for men and women are associated with their different patterns of doing research. Firstly, women scientists are inclined to do research in a more collaborative way than men. This may also explain why we observe fewer changes of research directions for women, as nonleading papers are not included when calculating *ChangeDegree*. Collaboration is also a good way to reduce the negative effects on publication and citation performance caused by changing research direction, which may partly explain women's fewer negative effects in this process. Secondly, gender differences in citation patterns and practices might also affect the research performance after a scientist enters a new field. Men self-cite and self-promote more often than the women (Livas, Delli, & Pandis, 2021), so that they can boost the visibility of their prior work and then inflate professional authority in the long run (Azoulay & Lynn, 2020). However, it might be less common for men to cite themselves after they change research direction and enter a new field, due to the different research contents. This might explain why their research performance is more negatively affected by such changes.

4.3. Implications

Our results and the discussion above have implications for research practice, policymaking, and (more broadly) for research priorities.

Firstly, we find, on the one hand, that changes of research direction decrease the productivity and citation impact of the publications where the scientist appears in the leading roles as the first or corresponding author. The reasons for this seem to be complex. Scientists who change their research direction face not only a possible decline in research performance according to bibliometric indicators, but also administrative and cultural barriers as well as sponsorship challenges (Lawson & Soós, 2014). As a remedy, grants and training programs could be provided to facilitate transitions and reduce the barriers to enter a new area. However, currently, although there have been some initiatives to support research and individuals to cross the boundaries of disciplines and to integrate the knowledge, the evaluation criteria for the development of scientific careers (i.e., field-oriented review of funding and tenure track) are more favorable for specialized and experienced scientists, thus creating a bias against more broadly oriented scientists. Our observation of different consequences by gender from change of research directions adds to the understanding of gender gaps in academia.

Under this circumstance, scientists who engage in changes of research directions need more supportive measures from multiple stakeholders. We suggest setting a more secure base for those scientists who enter a new field or subfield. Our results show that changes of research direction are associated with a decline in overall research performance as measured by bibliometric indicators. Hence, governments and funding agencies need to re-evaluate the criteria for resource allocation to support and encourage scientists to freely renew their research direction. Specifically, there should be more emphasis on the contributions and broader impact of publications than on the number and citations of publications. There should also be awareness that the traditional quantitative criteria, if applied, are comparing underrepresented and disadvantaged individuals to majorities with advantages. But it should be noted that this support should be set to capture the impact and outputs more effectively, rather than rejecting the criteria for them. We also learn from our study that the effects of research direction changes on research performance are persistent and vary with time. In this process, scientists may experience the loss of expertise, funding, and reputation in the original field. Thus, the assessment of individuals should encompass long-term performance evaluations and leave more time for scientists to complete the transition period. Moreover, it takes time for scientists to build expertise in a new subfield, let alone establishing new collaborations with researchers in new subfields. Also, moving into new subfields may distract scientists from their existing collaboration with colleagues in the original fields. In response to this situation, it would be helpful to encourage collaboration between different disciplines to enhance the exchange of ideas, methods, and theories, thereby stimulating exploratory research and enriching existing research agendas. Institutions can also create collaborative networks and organizations to encourage new interdisciplinary collaboration and maintain the existing collaborations.

Our study has focused on scientists changing their research direction with a proposal for a series of initiatives to support those making the change. However, this does not imply a negative view of being persistent on researching one or several topics. Being specialized is essential for the advance of science (Casadevall & Fang, 2014). But as previous studies have uncovered, specialization is a double-edged sword (Jain & Mitchell, 2022; Kuhn, 1963). More interdisciplinary and boundary-crossing research is indispensable for the sustained development of science. Meanwhile, specialized scientists are more often rewarded, while broad-based scientists are faced with more difficulties (Abramo et al., 2019; Leahey, 2006). As our results reveal, there is a trade-off between the specialized and diversified research strategies. It is important that policymakers support both types of careers and avoid gender bias in the choice between them.

Compared to other STEM fields (i.e., science, technology, engineering and mathematics), physics lags behind on numerous measures of gender equity, such as undergraduate and doctoral degrees granted to women (Porter & Ivie, 2019; Skibba, 2019), the proportion of women faculty (Skibba, 2019), and the global publication output by women (Holman, Stuart-Fox, & Hauser, 2018). Our study contributes to a deeper understanding of gender imbalances in physics. The aspect of changing research direction has hardly been mentioned in previous studies. Beyond physics, there are also consistent results in the higher education field finding that women scientists prefer less risky research agendas (Santos et al., 2021). Considering the limited number of previous studies focusing on gender differences in research direction changes, it would be interesting to see whether the same observations could be made in other fields, especially for those with a different structure of subfields or smaller gender gaps. Currently, we should be cautious when applying the results of this study to fields beyond physics. It would be interesting to see our new indicators of changes in research direction as part of career development applied to other fields of research.

This study has several limitations. First, considering that our data set is limited to physics, we cannot confirm that the findings of this study can be fully applied to other fields beyond physics. Further research is needed to verify the findings in other fields using various data sets. In addition, the data for this study is restricted to articles published in physics, as the focus of this study is on gender differences in research direction changes within the same research community. To make variables in this study more comparable, scientists who changed their research direction beyond physics are not included. We could also investigate further the robustness of this study's results by exploring the sensitivity of our conclusions to the granularity of the classification used (e.g., the CWTS article-level classification). This procedure would clarify the differences between research direction changes at various levels, making it more feasible to develop normalized indicators for fairer comparisons in gender issues. Another topic for further studies is how changing research directions leads to innovation and breakthrough results, which will be the next step of our studies (Qi, Zhou et al., 2024). As a second limitation, survivorship bias is an unknown factor that cannot be captured through publication data. Scientists who change research direction but fail to publish in new subfields are not visible in the data. Lastly, the concept of gender in this study is limited to a binary classification (i.e., men and women) due to the constrained technical methodology of gender inference.

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AUTHOR CONTRIBUTIONS

Lin Zhang: Conceptualization, Funding acquisition, Methodology, Supervision, Writing—original draft, Writing—review & editing. Fan Qi: Conceptualization, Formal analysis, Methodology, Software, Writing—original draft, Writing—review & editing. Gunnar Sivertsen: Writing—original draft, Writing—review & editing. Liming Liang: Conceptualization, Methodology. David Campbell: Methodology, Software, Writing—review & editing.

COMPETING INTERESTS

The authors have no competing interests.

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DATA AVAILABILITY

The data used in this study was provided by the International Center for the Study of Research (ICSR) Lab at Elsevier, a cloud-based computational platform. Access to this data is restricted, as it was used specifically for the peer-reviewed project conducted in the current study and is not publicly accessible. The code and scripts used in the analysis are available upon request from the corresponding author.

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