Does gender structure influence R&D efficiency? A regional perspective

Kou, M., Zhang, Y., Zhang, Y., Chen, K., Guan, J. & Xia, S.

Original citation & hyperlink:
Kou, M, Zhang, Y, Zhang, Y, Chen, K, Guan, J & Xia, S 2020, 'Does gender structure influence R&D efficiency? A regional perspective' Scientometrics, vol. 122, no. 1, pp. 477-501.
https://dx.doi.org/10.1007/s11192-019-03282-x

DOI 10.1007/s11192-019-03282-x
ISSN 0138-9130
ESSN 1588-2861

Publisher: Springer

The final publication is available at Springer via http://dx.doi.org/10.1007/s11192-019-03282-x

How Does Gender Structure Influence R&D Efficiency?

Abstract: The gender structure in research and development (R&D) activities has received more and more attention in terms of its importance in R&D management, but it is still not clear what the R&D efficiency discrepancy is between female and male personnel and how the gender structure of them affects R&D efficiency. Based on the regional-level dataset of China′ s research institutes, this study has used four types of R&D outputs (Papers, Books, Patents and Standards) together or individually in measuring R&D efficiency score to reveal this topic. When four types of R&D outputs are jointly considered, this paper applies the multi-output stochastic frontier analysis and finds that the higher proportion of male R&D personnel leads to higher R&D efficiency in general. Nevertheless, in terms of science and technology (S&T) papers or S&T books as single R&D output, we find that the higher proportion of female R&D personnel benefits higher R&D efficiency. On the contrary, R&D efficiency is lower with a higher proportion of female R&D personnel when the single R&D output is measured by invention patents application or national/industrial standards, respectively. Our findings to some degree indicate that the female R&D personnel are more effective in conducting scientific research activities, while their counterparts are more effective in doing technology development activities.

Key words: R&D efficiency; gender structure; gender gap; China’s research institutes

1. Introduction

The determinants of research and development (R&D) efficiency has become a research hotspot in academia (e.g., Chen and Guan, 2012; Fritsch and Slavtchev, 2007, 2010, 2011; Wang and Huang, 2007; Broekel, 2012, 2015). The extant literature classifies the determinants that influence R&D efficiency into the external and internal ones. More specifically, the external determinants include such as national regime, government subsidy, financial support, external cooperation or network, fiscal incentive policies and so on, and the internal determinants include such as internal collaboration or network, allocation of R&D expenditure, gender gap of R&D personnel and so on. Currently, most of the extant literature focuses on the effects of external variables on R&D efficiency, while limited attention is paid to the internal variables' effects. An interesting internal variable, namely, the gender structure of R&D personnel in the proportion of female or male R&D personnel, has been largely neglected in the extant literature. As a result, relatively little is known about what the R&D efficiency gap between females and males is in the science and technology (S&T) field and how the gender structure influences the R&D efficiency.

The gender differences or gap in S&T field have been explored in some recent literature such as Ceci et al. (2013) in research and academic career, Contini et al. (2017) in mathematics achievement and Jappelli et al. (2017) in research evaluation. Besides, several literature (e.g., Frietsch et al., 2009; Hunt et al., 2013; De, 2013; Jung and Ejermo, 2014; Meng, 2016) researched the gender gap in patenting or/and publishing from the R&D output perspective. The extant literature did not explore the gender gap in R&D efficiency related to the input-output relationship of R&D activities. In terms of relevant topics, the impact of the gender structure on R&D efficiency is an important subject for policy-makers and academic researchers.

To have a more comprehensive and rigorous understanding of how the gender structure influences R&D efficiency, this study adopts multiple types of R&D outputs together or individually to measure the R&D efficiency score. It is well known that R&D can split into two subgroups: science research and technology development (Lo, 2010). The former is about the discovery of truth in basic research activities, whilst the latter is about the application of truth in technology development activities (Pinch and Bijker, 1984). Correspondingly, the S&T papers and books are deemed as the outputs of scientific research activities, while the invention and application of patents and national/industrial standards are considered as the outputs of technology development activities. This study will explore the difference in the impact of gender structure on R&D efficiency for different R&D outputs. We will first explore whether the male and female R&D personnel have divergent R&D efficiency scores measured by different types of R&D outputs. If it is the case, then what exactly is the status of the gender gap in R&D efficiency and how it, reflected by the gender structure, affects the R&D efficiency in different S&T fields.

This study makes two significant contributions. First, this study proposes a new topic which is to explore the impact of the gender structure of R&D personnel on R&D efficiency in different S&T fields from the input-output transformation perspective. This study riches the literature about the gender gap in S&T studies. Second, this paper is an exploratory study introducing a modified method to measure the R&D efficiency with multiple types of R&D outputs. This riches the literature about the assessment of R&D efficiency. More specifically, different from most of studies that adopt Data Envelopment Analysis (DEA) method to measure R&D efficiency and Tobit regression analysis to measure multiple outputs (e.g., Wang and Huang, 2007; Guan and Chen, 2012), this study adopts multi-output Stochastic

Frontier Analysis (SFA) to overcome the shortcoming of DEA in time series. This try also extends the relevant literature based on the one-output SFA (e.g., Fu and Yang, 2009; Fritsch and Slavtchev, 2010).

The rest of this study is structured as follows. Relevant concepts, research frames and gender gap theories will be introduced in the second section. Section three will introduce the data source and economic model. The fourth section focuses on the empirical analysis. The conclusions and discussions are presented in the last section.

2. Theoretical Context

Endogenous growth model (Romer, 1986) reveals that S&T is the main driver to the long term economic growth. With significant numbers of resources devoted to S&T, how to increase R&D efficiency has become an important subject for policy-makers and academic researchers. In this situation, the determinants of R&D efficiency have been deemed as a critical index to evaluate the performance of R&D activities (Fritsch and Slavtchev, 2010). R&D efficiency reflects the transformation process from R&D input to R&D output (Cefis and Marsili, 2011), which is also called as knowledge production process. Knowledge production model originates from knowledge production function, which was proposed by Griliches (1979) to simulate knowledge-producing process and to study the effect of R&D and spillover. Existing studies consider the R&D process as a knowledge production process and, to measure the process, one specific production function, namely, the standard production function, is introduced as the analysis model and add specialized elements on this function to examine their effects on the R&D process (e.g., Fritsch and Slavtchev, 2007, 2010; Cefis and Marsili, 2011).

The standard production function is based on one hypothesis that all production units own the same production technology and the resource is allocated optimally. In this case, equal outputs will be gained if the inputs are equal and the inefficiency is not considered. However, Kumbhakar and Lovell (2000) found that the same inputs don't necessarily produce the same account of outputs even if all the units own the same production technology. The reason is that the production process is jointly affected by both external factors, such as, regime circumstance, finance circumstance, policy circumstance, as well as the internal factors such as the input structure. Similar to the production function, R&D is also one type of economic activity and, therefore, is jointly affected by both internal and external factors. Naturally, the discrepancy of those factors will lead to the different efficiencies of innovation unit (Furman et al., 2000; Li, 2009). The gender structure of R&D personnel is an internal factor and its influence on R&D efficiency can be explained by either the biological perspective, such as gene and brain, or the social perspective, including social burden and social bias.

From a social perspective, the main obligation of females is traditionally considered as taking care of their family (Frietsch et al., 2009), which usually leads females to devote less time on work (Greenhaus and Beutell, 1985; Jacobs and Gerson, 2004; Nomaguchi, 2009; Zhang et al., 2008). Nevertheless, with the development of society, last decades witnessed a significant increase in females' involvement in higher education as well as R&D (Leemann, 2010). Many studies, however, find that there still exists a significant gender gap in moving up in the academic career ladder. For instance, females are more likely to face barriers in their career than males (McWhirter, 1997), and have less access to academic resources and social capital (Leemann, 2010). In addition, female researchers have less geographically mobility than their male counterparts in general (Mcbrier, 2003).

From a biological perspective, gender differences in personality traits between males and females have been documented consistently for Neuroticism, Agreeableness, Extraversion, Conscientiousness, Openness and Intellect (Goodwin and Gotlib, 2004; Baron-Cohen et al., 2001), which may affect the R&D output discrepancy between female and male personnel. Many studies find that there is a big difference between male and female in the brain structure (Allen et al., 2003; Chen et al., 2007; Ruigrok et al., 2014) as well as brain function (Andreason et al., 1994; George et al., 1996; Kawachi et al., 2002; Bell, 2006). This difference in brain usually results in a gender gap in cognition ability (Yang et al., 2015), which influences the forming of perceptual views and solutions for problems (Dutton and Duncan, 1987). For example, some studies conclude that the male has better spatial cognition ability while the female’s lingual ability, such as speaking and writing, is better (Claster and Blair, 2013). Furthermore, there are gender differences in the ability of calculation, induction as well as STEM (Science Technology Engineering and Mathematics). For example, Contini et al. (2017) find that there is an obvious gender gap in mathematics score and girls usually have less self-confidence and more stress in math related activities (Lubienski et al., 2013; Twenge and Campbell, 2001). This phenomenon exists in almost every family structure, ethnic group, and level of the socio-economic distribution (Fryer and Levitt, 2010).

Due to the significant gender differences, male and female personnel might have different advantages and disadvantages of producing different types of R&D outputs, such as invent patents, S&T papers, S&T books and National/Industrial standards. This study will explore how the gender structure of R&D personnel influences R&D outputs in given R&D inputs, namely R&D efficiency.

3. Methods

3.1 Estimation method

R&D efficiency reflects the transform effectiveness from R&D inputs to outputs, and this study will analyze how this transform effectiveness is affected by the gender structure of R&D personnel. For the research purpose, many studies adopt DEA-regression method in which DEA is adopted to measure efficiency and regression analysis is used to examine efficiency factors (Guan and Chen, 2012; Liu et al., 2017; Watcharasriroj and Tang, 2004). DEA is a non-parameter method for which a specific kind of production function form is unnecessary. Another advantage, when compared with the traditional one-output SFA, is that it is still effective when measuring multiple R&D outputs. However, DEA is not effective for time series data. Besides, the measurement results of R&D efficiency based on DEA is much susceptible when data lies in the frontier. Further, the efficiency estimation is insensitive to data and may change with small error in some frontier data (Tavana et al., 2014). To overcome these limitations, this study adopts SFA (e.g., Fritsch and Slavtchev, 2007, 2010, 2011; Broekel, 2012, 2015) rather than DEA-regression.

In terms of multiple outputs (including (Papers, Books, Patents and Standards), a multi-output SFA model is introduced to reveal the impact of the gender gap on R&D efficiency. The traditional one-output SFA model can overcome the drawbacks of DEA, but it is not applicable for measuring multiple outputs (Henningsen et al., 2015; Löthgren, 1997). To overcome this weakness, this study follows Löthgren (1997)'s proposition and adopts a multi-output SFA model, which adds the concept of Shephard Distance Function to SFA. In addition, when measuring a single output, this study adopts the single-output SFA model developed by Battese and Coelli (1995).

It should be noted that the formulation of SFA includes two functions. One is the frontier function for efficiency estimation and the other is the inefficiency function for exploring technical inefficiency factors. Battese and Coelli (1995) applied maximum likelihood estimator to estimate the parameter of frontier function and then calculated σ and γ based on the two formulas: $\sigma^2=\sigma^2_v+\sigma_u^2$ and $\gamma=\sigma_u^2/(\sigma_v^2+\sigma_u^2)$. When there is no technical inefficiency, e.g., γ=0, the ordinary OLS method is appropriate. Therefore, we need to test whether γ is equal to 0 or not. The SFA is suitable for this study only when γ≠0 is significant.

In the implementation of our analyses, we follow previous studies (e.g., Chen and Kou, 2014; Chen et al., 2017; Schilling and Phelps, 2007) and calculate models lagging for 0, 1,2 and 3 years to reduce simultaneity problems and to enhance the robustness of regression results. Then, this paper will implement twenty SFA models for five kinds of R&D outputs.

3.2 Variables and Data Source

The research institutes, as a typical R&D organization, are devoted to R&D activities. So, it is closely appropriate to use research institutes as our research sample. Besides, the research institutes are a critical driver in pushing S&T research in China (Chen et al., 2017), and this study adopts the regional-level dataset of China's research institutes to implement our analyses. The data cover twenty nine provinces in total. Eleven of them belong to eastern and coastal regions, i.e., Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan and Hebei. The rest eighteen provinces are inland regions, including, Chongqing, Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, Sichuan, Guizhou, Yunnan, Shannxi, Gansu, Ningxia and Xinjiang. Due to insufficient data, our sample does not include Tibet and Qinghai.

R&D inputs and outputs are two indispensable variables of measuring R&D efficiency in the knowledge production process. Specifically, R&D manpower and knowledge stock are significantly related to R&D inputs (Guan et al., 2016; Wang and

Huang, 2007). To measure R&D manpower, extant studies usually take full-time equivalent R&D personnel (e.g., Chen and Kou, 2014) or the number of real R&D personnel (e.g., Fu and Yang, 2009; Chen and Guan, 2012) as an approximation. To ensure the data availability and consistence with the gender structure of R&D personnel, this study adopts the number of real R&D personnel to measure the R&D manpower input. With respect to the knowledge stock, it is almost impossible to count it precisely (Ahammad et al., 2016). Therefore, many researchers take R&D capital stock as a substitution of R&D knowledge stock (Beneito and Sanchis, 2015; Goto and Suzuki, 1989; Hall and Mairesse, 1995). To calculate R&D capital stock , many studies adopt capital inventory method put forward by Griliches(1979), which is proved to be effective (Goto and Suzuki, 1989; Hall and Mairesse, 1995). Therefore, this study takes a capital inventory method to calculate R&D capital stock in the base period. The formula is presented below.

$$K_{it} = (1-\delta_{it})K_{it-1} + R_{it} \quad (i = 1, 2, ...N; t = 1, 2, ...T) \tag{1}$$

Where K_{it} denotes the R&D capital stock of object i in period t; K_{it-1} is the R&D capital stock of object i in period $t-1$;δ denotes the rate of depreciation; R_{it} denotes the R&D capital input of object i in period t.

To calculate K_{it}, two issues need to be solved: how to calculate R&D capital stock in the base period; how to deduct inflation of R&D capital. To solve the first issue, this study adopts the method used by Goto and Suzuki (1989), which assumes the average growing rate of R&D capital input is constant when K_{it-1} is calculated and the formula is presented below:

$$K_{i0} = R_{i0} / (g + \delta) \tag{2}$$

Where g denotes the average growing rate of R&D capital input; δ denotes the rate of depreciation; R_{i0} denotes the R&D capital stock in the base period. g can be calculated by using R&D capital input subtracting the labor cost, which is contained in R&D capital input after eliminating inflation. With the above approach, this study can gain the R&D capital stock in the base period. As for the second issue, the inflation index can be calculated by the sum weighted consumption index and the fixed capital index, which is easy to eliminate inflation in R&D capital.

When it comes to the R&D output, researchers mainly use either invent patents or revenues of new products to measure it (Cheung and Ping, 2004; De, 2013; Hunt et al., 2013; Jung and Ejermo, 2014; Siegel et al., 2003). Research institutes are the critical knowledge creators and have long been serving as important sources of scientific and technical knowledge (Chen et al., 2017), Research institutes produce scientific research outputs (e.g., S&T papers and books), as well as technology development outputs (e.g., Invent Patents, and National/Industrial Standards). Although copyrights, non-codified knowledge and other informal information are outputs of research institutes, their data source is unavailable in many cases (Zhang et al., 2016). For this reason, this study only adopts research institutes' available and tangible R&D outcomes with codified knowledge, including S&T papers (PAP), S&T books (BOO), Invent Patents (PAT), and National/Industrial Standards (STA). Among the four types R&D outputs, the first two are the typical scientific research outputs, while the latter two usually result from technology development activities. The four R&D outputs are measured by the absolute number respectively. It should be noted that the Invent Patents (PAT) is measured by the number of invent patent application rather than invent patent granting since invent patent application is less vulnerable to the working efficiency than invent patent granting and can reflect the real R&D outputs more objectively (Yue, 2008).

The core variable in this study is the gender structure of R&D personnel (GENDER), which is measured by the ratio of the number of female R&D personnel to the total number of R&D personnel.

Most variables are uncontrollable in the R&D process (Chen and Kou, 2014), which will promote or hinder R&D efficiency. This study follows previous region-level studies (Furman et al., 2000; Fritsch and Slavtchev, 2007; Li, 2009) and controls some variables that may affect the R&D efficiency. These variables include the department structure of R&D personnel (measured by the ratio of the number of R&D personnel in basic research department (DEP_1) to the number of R&D personnel in applied research department (DEP_2)), GDP per person (PGDP), education input per person (PEDU) and so on. In terms of the R&D efficiency discrepancy between regions, this paper considers the geographical influences. This study introduces a dummy variable, Eastern and Coastal Region (ECR), and sets its value as 1 if one region belongs to eastern and costal regions with relative developed economy and industry conditions. The definition and calculation of variables are presented in Table 1.

Table 1. Definition and Calculation of Variables

Variables	Sign	Definition and Calculation
S&T Papers	PAP	Number of papers published on foreign journals yearly
S&T books	BOO	Number of S&T books published yearly
Invent Patents Application	PAT	Number of invent patent application yearly
National/Industrial Standards	STA	Number of national or industrial criteria made yearly
Norm of Multiple R&D Output	Norm	The norm of PAP, BOO, PAT and STA
R&D Labor Input	L	Number of R&D personnel
R&D Capital Input	K	The stock of R&D capital

Gender Structure of R&D personnel	GENDER	Proportion of female R&D personnel to total R&D personnel
Proportion of R&D Personnel Being Engaged in Applied Research	DEP_2	Proportion of R&D personnel Being Engaged in applied Research to total R&D personnel
GDP Per Person	PGDP	GDP divided by the number of population
Education Investment Per Person	PEDU	Education fee divided by the number of population
Easter and Costal Region	ECR	It's 1 if the district belongs to Eastern and Costal Region(ECR)

The data of most variables mainly comes from *China Statistical Yearbook on Science and Technology*. The data of some variables, e.g., price index, education investment and GDP, comes from *China Statistical Yearbook*. The data in this study are traced back to year 2009, based on their availability. The descriptive statistic of panel data used in this study is listed in table 2, which includes all R&D input and output variables, the gender structure of R&D personnel variable and other important control variables. There are in total 174 sets of observations from 2009 to 2014.

Table 2. Descriptive Statistic (n=174)

Variables	Average Value	STD	Minimum	Maximum
LnPAP	5.927	1.662	0.000	9.870
LnBOO	4.417	0.948	1.099	7.658
LnPAT	5.757	1.342	1.946	9.186
LnSTA	3.743	1.247	0.000	8.098
LnNorm	6.344	1.284	2.221	9.992
LnL	8.888	1.071	5.956	11.602
LnK	13.507	1.368	9.524	16.957

GENDER	0.320	0.048	0.039	0.444
DEP1	0.163	0.095	0.011	0.483
DEP2	0.357	0.092	0.116	0.657
Ln(PGDP)	10.440	0.465	9.245	11.442
Ln(PEDU)	7.227	0.369	6.559	8.337

4. Empirical Analyses

This section will present statistical results for twenty SFA models with the time lag of 0, 1, 2 and 3 years for five types of outputs, respectively to display how the gender structure of R&D personnel affects the R&D efficiency (See tables 3-7). For most models, the $\gamma \neq 0$ is significant, which confirms the existence of technical R&D inefficiency and the justification for adopting SFA estimation.

4.1 Empirical analysis in the condition of multiple types of R&D outputs

The empirical results presented by Table 3 show that the gender structure of R&D personnel significantly affects R&D efficiency in terms of multiple outputs.

Table 3. Effect of gender structure on the comprehensive R&D efficiency for multiple types of R&D outputs

Coefficients	No time lag		Lag for 1 year		Lag for 2 years		Lag for 3 years	
	Model 1		Model 2		Model 3		Model 4	
Frontier function								
constant	-2.513***	(-6.132)	-1.637***	(-4.278)	-1.752***	(-2.516)	-0.736	(-1.492)
lnL	0.483***	(3.141)	0.978***	(8.463)	1.080***	(3.989)	1.315***	(10.071)
lnK	0.373***	(3.318)	-0.020	(-0.211)	-0.026	(-0.125)	-0.293***	(-2.597)
Inefficiency function								
constant1	11.742***	(4.243)	10.007***	(6.592)	1.289	(1.207)	8.306***	(4.180)
GENDER	2.251	(1.415)	2.236***	(2.532)	0.733*	(0.722)	2.896***	(2.486)

DEP1	-4.046***	(-2.638)	-2.633***	(-3.691)	-0.975	(-0.992)	-3.151***	(-3.396)
DEP2	1.220	(1.484)	0.551	(1.352)	0.481	(0.495)	0.395	(0.709)
Ln(PGDP)	-0.323	(-0.957)	-0.297	(-1.737)	0.575***	(3.371)	-0.162	(-0.711)
Ln(PEDU)	-1.132**	(-2.214)	-0.923***	(-3.942)	-0.842***	(-2.910)	-0.922***	(-2.697)
ECR	-0.446	(-1.864)	-0.278***	(-2.690)	-0.427***	(-3.259)	-0.411***	(-2.706)
σ^2	0.404***	(4.027)	0.129***	(6.585)	0.160***	(4.665)	0.120***	(4.973)
γ	0.947	(34.982)	0.881***	(13.529)	1.000***	(6.448)	0.861***	(8.153)
ols-log	-130.434		-101.755		-77.913		-56.431	
log	-83.079		-36.217		-51.831		-16.307	
LOG	-73.688		-43.024		-30.128		-21.393	
LR	94.709		131.076		52.164		80.247	

Note: ***, ** and * denotes the significant level of 1%, 5% and 10% respectively.

The finding suggests that the R&D efficiency of male researchers differs significantly from that of female researchers. This may derive from the significant difference in the brain structures as well as family responsibilities between male and female. In the models that contain the gender structure of R&D personnel with time lag of 1, 2 and 3 years, respectively (as shown by the models 2, 3 and 4), the coefficient of the gender structure of R&D personnel is positive and significant. Clearly, the proportion of female R&D personnel to the whole number of R&D personnel is positively related to the technological inefficiency item of Stochastic Frontier Model, indicating the gender structure of R&D personnel is negatively related to the comprehensive R&D efficiency. In other words, the higher proportion of female R&D personnel results in the lower R&D efficiency. This denotes that the comprehensive R&D efficiency of female researchers is lower than that of the male researchers.

4.2 Empirical analysis on each single type of R&D outputs

The previous sections prove that there indeed exists a discrepancy in R&D efficiency between the male and female, but the findings are based on the measurement of multiple types of R&D outputs, which might cover up some details. For example, when female researchers have a stronger ability in producing one single type of R&D outputs, the measurement of multiple types of R&D outputs might be invalid. Therefore, it is necessary to further investigate how the gender structure affects R&D efficiency from the perspective of each single type of R&D outputs.

4.2.1 Invent Patent Application

This section will examine how the gender structure of R&D personnel affects the R&D efficiency in the case of invent patent application as R&D output, and the regression result is presented in Table 4.

Table 4. Effect of gender structure of R&D personnel on R&D efficiency in the case of invent patent application as R&D output.

Coefficients	No time lag		Lag for 1 year		Lag for 2 years		Lag for 3 years	
	Model 5		Model 6		Model 7		Model 8	
Frontier function								
constant	-3.290***	(-8.052)	-2.178***	(-4.851)	-2.017***	(-4.109)	-1.800***	(-2.449)
lnL	0.227**	(2.072)	0.746***	(5.573)	0.881***	(6.225)	1.028***	(4.575)
lnK	0.599***	(6.808)	0.185	(1.735)	0.089	(0.810)	-0.020	(-0.134)
Inefficiency function								
constant	9.357***	(5.219)	7.548***	(4.567)	5.899***	(3.410)	3.870*	(1.828)
GENDER	1.079	(1.047)	2.120**	(2.255)	2.457***	(2.386)	2.998***	(2.407)
DEP1	-2.667***	(-4.100)	-2.685***	(-4.424)	-2.653***	(-3.966)	-2.305***	(-3.332)
DEP2	0.999 **	(2.041)	0.846*	(1.895)	1.071**	(2.172)	1.069	(1.371)
Ln(PGDP)	-0.468***	(-2.302)	-0.403**	(-2.133)	-0.327	(-1.618)	-0.047	(-0.220)
Ln(PEDU)	-0.537*	(-1.853)	-0.412	(-1.568)	-0.329	(-1.105)	-0.506	(-1.396)
ECR	-0.293***	(-2.349)	-0.370***	(-3.392)	-0.508***	(-4.220)	-0.624***	(-3.120)

σ^2	0.197***	(6.005)	0.147***	(6.165)	0.125***	(5.348)	0.110***	(3.075)
γ	0.835***	(11.295)	0.776***	(6.333)	0.675***	(3.357)	0.442	(0.629)
ols-log	-136.680		-104.848		-78.594		-55.839	
Log	-76.286		-49.587		-32.293		-22.291	
LR	120.789		110.523		92.601		67.095	

Note: ***, ** and * denotes the significant level of 1%, 5% and 10% respectively.

As shown by the models 6, 7 and 8, we find that the coefficient of the gender structure is positively and significantly related to the technological inefficiency item of SFA with the time-lag of 1~3 years, suggesting the larger the proportion of female researchers is, the lower the R&D efficiency is. In other words, there is a negative relationship between the gender structure of R&D personnel and R&D efficiency, indicating the male researchers have a higher efficiency than female researchers in conducting invent patent application.

4.2.2 S&T Papers

This section will examine how the gender structure of R&D personnel affects the R&D efficiency in the case of S&T papers as R&D output, and the regression result is presented in Table 5.

Table 5. Effect of gender structure of R&D personnel on R&D efficiency in the case of S&T papers as R&D output

Coefficients	No time lag		Lag for 1 year		Lag for 2 years		Lag for 3 years	
	Model 9		Model 10		Model 11		Model 12	
Frontier function								
constant	0.847***	(3.356)	2.049***	(5.797)	1.490*	(2.282)	2.322***	(4.503)
lnL	0.541***	(5.248)	0.854***	(9.498)	0.732***	(4.521)	0.945***	(7.677)
lnK	0.224***	(2.629)	-0.060	(-0.720)	0.059	(0.394)	-0.132	(-1.135)

Inefficiency function								
constant	0.212	(0.145)	1.653	(1.739)	1.361	(1.353)	1.765	(1.642)
GENDER	-2.228***	(-2.347)	-0.619*	(-0.692)	-1.281*	(-1.211)	-1.288*	(-1.563)
DEP1	-2.513***	(-3.668)	-2.173***	(-4.318)	-2.445***	(-5.427)	-2.023***	(-2.483)
DEP2	1.180***	(2.626)	1.048***	(3.156)	1.243***	(3.323)	0.717	(1.237)
Ln(PGDP)	0.384*	(1.979)	0.193	(1.361)	0.233	(1.267)	0.282	(1.017)
Ln(PEDU)	-0.415*	(-1.965)	-0.387***	(-2.357)	-0.397	(-1.729)	-0.490	(-1.233)
ECR	-0.513***	(-3.937)	-0.425***	(-5.800)	-0.480***	(-4.971)	-0.376***	(-2.836)
σ^2	0.132***	(6.349)	0.083***	(5.982)	0.093***	(4.961)	0.080***	(3.503)
γ	0.900***	(6.720)	1.000***	(>100)	1.000***	(>100)	1.000***	(>100)
ols-log	-90.307		-64.544		-51.569		-38.671	
log	-40.272		-10.331		-5.284		-2.979	
LR	105.606		108.426		92.569		71.384	

Note: ***, ** and * denotes the significant level of 1%, 5% and 10% respectively.

As shown in the models 9, 10, 11 and 12, we find that the gender structure is negatively and significantly related to the technological inefficiency item of SFA with the time-lag of 1~3 years, which means that the higher proportion of female R&D personnel results in the lower R&D inefficiency. In other words, the female researchers have a higher R&D efficiency in publishing S&T papers than their male counterparts.

4.2.3 S&T books

This section explores how the gender structure of R&D personnel affects R&D efficiency in the case of S&T books as R&D output, and the regression result is presented in Table 6.

Table 6. Effect of gender structure of R&D personnel on R&D efficiency in the case of S&T books as R&D output

Coefficients	No time lag		Lag for 1 year		Lag for 2 years		Lag for 3 years	
	Model 13		Model 14		Model 15		Model 16	
Frontier function								
constant	-1.990***	(-3.054)	-0.299	(-0.474)	-0.253	(-0.540)	0.532	(0.982)
lnL	0.333*	(1.970)	0.973***	(4.682)	0.890***	(4.140)	1.062***	(4.255)
lnK	0.319***	(2.439)	-0.179	(-1.103)	-0.138	(-0.830)	-0.305	(-1.552)
Inefficiency function								
constant	2.600	(1.616)	2.185	(1.243)	1.087	(1.067)	2.686	(1.787)
GENDER	-3.531***	(-3.304)	-2.676*	(-1.323)	-0.759*	(-0.781)	-0.578*	(-0.597)
DEP1	-0.777	(-1.306)	-1.040	(-1.341)	-0.612	(-0.700)	-1.473	(-1.575)
DEP2	-0.043	(-0.088)	0.783	(1.454)	0.448	(0.499)	-0.240	(-0.343)
Ln(PGDP)	0.298	(1.353)	0.296	(1.580)	0.339	(1.228)	0.284	(0.948)
Ln(PEDU)	-0.497**	(-2.001)	-0.381	(-1.384)	-0.400	(-0.991)	-0.507	(-1.175)
ECR	-0.367***	(-3.094)	-0.536***	(-2.980)	-0.389***	(-3.426)	-0.250***	(-2.519)
σ^2	0.294***	(9.420)	0.243***	(6.364)	0.269***	(5.364)	0.261***	(4.461)
γ	0.005	(0.004)	1.000***	(36.842)	1.000***	(>100)	1.000***	(>100)
ols-log	-164.388		-125.619		-100.475		-74.646	
log	-140.284		-100.025		-83.772		-60.533	
LR	48.208		51.190		33.406		28.226	

Note: ***, ** and * denotes the significant level of 1%, 5% and 10% respectively.

As shown in the models 13, 14, 15 and 16, we find that the gender structure of R&D personnel is negatively and significantly related to the technological inefficiency item of SFA. This means that the larger proportion of female researchers can reduce the R&D inefficiency. In other words, the gender structure of R&D personnel is positively correlated to the R&D efficiency, indicating the female researchers are more efficient than their male counterparts in publishing S&T books.

4.2.4 National/Industrial Standards

The regression result about how the gender structure of R&D personnel affects R&D efficiency in the case of National/Industrial Standards as R&D output is presented in Table 7.

Table 7. Effect of gender structure of R&D personnel on R&D efficiency in the case of National/Industrial Standards as R&D output

Coefficients	No time lag		Lag for 1 year		Lag for 2 years		Lag for 3 years	
	Model 17		Model 18		Model 19		Model 20	
Frontier function								
constant	-1.119	(-1.706)	-0.949	(-1.728)	-0.074	(-0.074)	0.961	(0.805)
lnL	0.452	(1.789)	1.273***	(4.435)	0.852***	(2.832)	1.257***	(3.665)
lnK	0.240	(1.166)	-0.335	(-1.458)	-0.097	(-0.376)	-0.436	(-1.621)
Inefficiency function								
constant	14.537***	(6.572)	12.976***	(7.997)	14.915***	(6.835)	15.647***	(7.011)
GENDER	2.512***	(2.500)	2.302**	(2.145)	2.323*	(1.106)	1.442*	(0.279)
DEP1	-3.218***	(-3.770)	-2.546***	(-2.576)	-3.194***	(-2.471)	-2.907***	(-2.973)
DEP2	-0.283	(-0.342)	-0.308	(-0.366)	0.337	(0.284)	-0.815	(-1.246)
Ln(PGDP)	-0.379	(-1.226)	-0.556	(-1.734)	-0.516	(-0.984)	-0.620*	(-1.877)
Ln(PEDU)	-1.225***	(-3.185)	-0.789*	(-1.953)	-1.108*	(-1.913)	-0.950**	(-2.225)
ECR	0.067	(0.357)	0.292	(1.449)	0.114	(0.748)	0.327*	(1.807)
σ^2	0.540***	(7.773)	0.525***	(5.344)	0.474***	(7.579)	0.337***	(6.629)
γ	1.000***	(>100)	1.000***	(>100)	1.000***	(>100)	1.000***	(>100)
ols-log	-223.805		-179.905		-147.145		-99.274	
log	-18.997		-152.288		-120.667		-75.223	
LR	67.658		55.234		52.958		48.102	

Note: ***, ** and * denotes the significant level of 1%, 5% and 10% respectively.

As shown in the models 17, 18, 19 and 20 where the gender structure of R&D personnel is included, we find that the coefficient of the gender structure of R&D personnel is positive and significant. This indicates that the larger the proportion of female researchers is, the higher the R&D inefficiency is. That is to say, the gender structure of R&D personnel is negatively correlated to the R&D efficiency, suggesting the male researchers are more efficient than their female counterparts in designing National/Industrial Standards.

5. Conclusions and Discussions

A significant amount of studies explore the statistical differences between females and males from social and biological perspectives (De, 2013; Hunt et al., 2013; Jung and Ejermo, 2014; McWhirter, 1997). However, little attention has been paid to the gender differences in R&D efficiency. Further, it is far from clear about how the gender structure of R&D personnel influences the R&D efficiency, especially when the R&D efficiency is measured by multiple types of R&D outputs. In this study, we take into account of four types of R&D outputs, and apply multiple-R&D-output-SFA as well as single-R&D-output-SFA to explore this issue. In this way, we make some comparisons on statistical differences between female and male R&D personnel in R&D efficiency, which ensures the robustness of research findings.

The findings suggest that the gender gap of R&D efficiency indeed exists. Female researchers are better at doing scientific research while their male counterparts are better suited to conducting technology development. Specifically, by adopting the single-R&D-output-SFA model where the R&D efficiency is measured by one single type of R&D output, we find that a higher proportion of female researchers is conducive to higher R&D efficiency when it is measured by the number of S&T papers and S&T books. Nevertheless, a higher proportion of female researchers results in a lower R&D efficiency when it is measured by the number of Invent Patents Application (IPA) and National/Industrial Standards. In addition, we find that a higher proportion of male researchers benefits the comprehensive R&D efficiency by adopting the multiple-R&D-output-SFA model where the R&D efficiency is measured jointly by four types of R&D outputs.

This study has important theoretical and methodological implications. First, it contributes to our better understanding on the internal determinants of R&D efficiency score. Different with most of the extant literature which usually focuses on the effects of external (environment) factors (e.g., Guan et al., 2016; Fritsch and Slavtchev, 2007, 2010), this paper explores the effects of internal factors (gender structure of R&D personnel) on R&D efficiency. Second, this paper enriches the literature about the gender gap in R&D performance. Different with the extant literature (De, 2013; Hunt et al., 2013; Jung and Ejermo, 2014; McWhirter, 1997) which reveals the gender gap in R&D output performance, e.g., patenting and publishing, our study provides evidence for the gender gap in R&D input-output process performance (i.e., R&D efficiency).

This study also has important policy implications. First, the findings of this study can be regarded a guidance to the design of research teams to improve their R&D efficiency. For instance, different types of research projects should choose an optimal gender structure of researchers. Second, this study finds that a higher proportion of male R&D personnel brings higher R&D efficiency in general. This might explain why females are placed in a disadvantage position when seeking access to R&D. Therefore, to increase gender equality in R&D activities, more policies should be developed to help female researchers reduce barriers and discrimination in R&D activities.

One limitation is that the macro-level data constraint this study from digging into some interesting research questions, such as the relationship between heterosexual cooperation advantages and R&D efficiency, as well as the relationship between ages and R&D efficiency and so on. Besides, the factors that might incur the gender gap in R&D efficiency, such as education background, marital status and age, deserve further exploration in future studies.

Reference

Agrell, P.J., Farsi, M., Filippini, M., Koller, M., 2014. Unobserved heterogeneous effects in the cost efficiency analysis of electricity distribution systems, The Interrelationship Between Financial and Energy Markets. Springer, pp. 281-302.

Ahammad MF, Tarba SY, Liu Y, Glaister K., 2016. Knowledge transfer and cross-border acquisition performance: Impact of cultural distance and employee retention. International Business Review 25(1), 66-75.

Aigner, D., Lovell, C.A.K., Schmidt, P., 1977. Formulation and estimation of stochastic frontier production function models. Journal of Econometrics 6(1), 21-37.

Allen, J.S., Damasio, H., Grabowski, T.J., Bruss, J., Zhang, W., 2003. Sexual dimorphism and asymmetries in the gray–white composition of the human cerebrum. Neuroimage 18(4), 880-894.

Andreason, P.J., Zametkin, A.J., Guo, A.C., Baldwin, P., Cohen, R.M., 1994. Gender-related differences in regional cerebral glucose metabolism in normal volunteers. Psychiatry Research 51(2), 175-183.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., Clubley, E., 2001. The autism-spectrum quotient (AQ): evidence from Asperger syndrome/high-functioning autism, males and females, scientists and mathematicians. Journal of autism and developmental disorders 31(1), 5-17.

Battese, G.E., Coelli, T.J., 1992. Frontier production functions, technical efficiency and panel data: With application to paddy farmers in India. Journal of Productivity Analysis 3(1), 153-169.

Battese, G.E., Coelli, T.J., 1995. A model for technical inefficiency effects in a stochastic frontier production function for panel data. Empirical economics 20(2), 325-332.

Bell, E.C., Willson, M.C., Wilman, A.H., Dave, S., Silverstone, P.H., 2006. Males and females differ in brain activation during cognitive tasks. Neuroimage 30(2), 529-538.

Beneito, P., Sanchis, A., 2015. The path of R&D efficiency over time. International Journal of Industrial Organization 42, 57-69.

Bi, K., Huang, P., Wang, X., 2016. Innovation performance and influencing factors of low-carbon technological innovation under the global value chain: A case of Chinese manufacturing industry. Technological Forecasting & Social Change 111, 275-284.

Broekel, T., 2012. Collaboration Intensity and Regional Innovation Efficiency in Germany—A Conditional Efficiency Approach, Industry and Innovation 19(2), 155-179.

Broekel, T., 2015. Do Cooperative Research and Development (R&D) Subsidies Stimulate Regional Innovation Efficiency? Evidence from Germany. Regional Studies, 49(7), 1087-1110.

Cefis, E., Marsili, O., 2011. Born to flip. Exit decisions of entrepreneurial firms in high-tech and low-tech industries. Journal of Evolutionary Economics 21(3), 473-498.

Chen, K.H., Guan, J.C., 2012. Measuring the Efficiency of China's Regional Innovation Systems: Application of Network Data Envelopment Analysis (DEA). Regional studies 46(3), 355-377.

Chen, K.H., Kou, M.T., 2014. Staged efficiency and its determinants of regional innovation systems: a two-step analytical procedure. Annals of Regional Science 52(2), 627-657.

Chen, K., Zhang, Y., Zhu, G., Mu, R., 2017. Do research institutes benefit from their network positions in research collaboration networks with industries or/and universities? Technovation, https://doi.org/10.1016/j.technovation.2017.10.005.

Chen, X., Sachdev, P.S., Wen, W., Anstey, K.J., 2007. Sex differences in regional gray matter in healthy individuals aged 44–48 years: A voxel-based morphometric study. Neuroimage 36(3), 691-699.

Cheung, K.-y., Ping, L., 2004. Spillover effects of FDI on innovation in China: Evidence from the provincial data. China Economic Review 15(1), 25-44.

Claster, P.N., Blair, S.L., 2013. Latino and Latina Educational Attainment: An Investigation of Bi-Lingual Language Abilities and the Familial Context. Sociological Viewpoints 29.

Ceci, S.J., Stephen, J., Ginther, D.K., Kahn, S., Williams, W.M., 2014. Women in academic science: a changing landscape. Psychological Science in the Public Interest 15 (3), 75-141.

Contini, D., Tommaso, M.L.D., Mendolia, S., 2017. The gender gap in mathematics achievement: Evidence from Italian data. Economics of Education Review 58, 32-42.

De, M.I., 2013. Patenting and the gender gap: should women be encouraged to patent more? Science & Engineering Ethics 19(2), 491-504.

Dutton, J.E., Duncan, R.B., 1987. The influence of the strategic planning process on strategic change. Strategic Management Journal 8(2), 103-116.

Frietsch, R., Haller, I., Funken-Vrohlings, M., Grupp, H., 2009. Gender-specific patterns in patenting and publishing. Research Policy 38(4), 590-599.

Fritsch, M., Slavtchev, V., 2007. What Determines the Efficiency of Regional Innovation Systems? Jena Economic Research Papers.

Fritsch, M., Slavtchev, V., 2010. How does industry specialization affect the efficiency of regional innovation systems? Annals of Regional Science 45(1), 87-108.

Fritsch, M., Slavtchev, V., 2011. Determinants of the Efficiency of Regional Innovation Systems, Regional Studies, 45(7), 905-918.

Fryer, R.G., Levitt, S.D., 2010. An Empirical Analysis of the Gender Gap in Mathematics. American Economic Journal: Applied Economics 2(2), 210-240.

Fu, X., Yang, Q.G., 2009. Exploring the cross-country gap in patenting: A Stochastic Frontier Approach. Research Policy 38(7), 1203-1213.

Furman, J.L., Porter, M.E., Stern, S., 2000. The determinants of national innovative capacity. Research Policy 31(6), 899-933.

George, M.S., Ketter, T.A., Parekh, P.I., Herscovitch, P., Post, R.M., 1996. Gender differences in regional cerebral blood flow during transient self-induced sadness or happiness. Biological Psychiatry 40(9), 859-871.

Goodwin, R.D., Gotlib, I.H., 2004. Gender differences in depression: the role of personality factors. Psychiatry Research 126(2), 135-142.

Goto, A., Suzuki, K., 1989. R&D Capital, Rate of Return on R&D Investment and Spillover of R&D in Japanese Manufacturing Industries. Review of Economics & Statistics 71(4), 555-564.

Greenhaus, J.H., Beutell, N.J., 1985. Sources of Conflict Between Work and Family Roles. The Academy of Management Review 10(1), 76-88.

Griliches, Z., 1979. Issues in Assessing the Contribution of Research and Development to Productivity Growth. Bell Journal of Economics 10(1), 92-116.

Guan, J.C., Chen, K.H., 2012. Modeling the relative efficiency of national innovation systems. Research Policy 41(1), 102-115.

Guan, J.C., Zuo, K.R., Chen, K.H., Yam, R.C.M., 2016. Does country-level R&D efficiency benefit from the collaboration network structure? Research Policy 45(4), 770-784.

Hall, B.H., Mairesse, J., 1995. Exploring the relationship between R&D and productivity in French manufacturing firms. Journal of Econometrics 65(1), 263-293.

Henningsen, G., Henningsen, A., Jensen, U., 2015. A Monte Carlo study on multiple output stochastic frontiers: a comparison of two approaches. Journal of Productivity Analysis 44(3), 309-320.

Hunt, J., Garant, J.P., Herman, H., Munroe, D.J., 2013. Why are women underrepresented amongst patentees? Research Policy 42(4), 831-843.

Ino, T., Nakai, R., Azuma, T., Kimura, T., Fukuyama, H., 2010. Gender Differences in Brain Activation During Encoding and Recognition of Male and Female Faces. Brain Imaging & Behavior 4(1), 55-67.

Jacobs, J.A., Gerson, K., 2004. The time divide : work, family, and gender inequality. Harvard University Press, Cambridge, MA.

Jappelli, T., Nappi, C.A., Torrini, R., 2017. Gender effects in research evaluation. Research Policy 46(5), 911-924.

Jung, T., Ejermo, O., 2014. Demographic patterns and trends in patenting: Gender, age, and education of inventors. Papers in Innovation Studies 86(86), 110-124.

Kawachi, T., Ishii, K., Sakamoto, S., Matsui, M., Mori, T., Sasaki, M., 2002. Gender differences in cerebral glucose metabolism: a PET study. Journal of the Neurological Sciences 199(1), 79-83.

Kumbhakar, S.C., Lovell, C.A.K., 2000. Stochastic frontier analysis. Cambridge University Press.

Löthgren M., 1997. Generalized stochastic frontier production models. Economics Letters, 57(3), 255-259.

Leemann, R.J., 2010. Gender inequalities in transnational academic mobility and the ideal type of academic entrepreneur. Discourse Studies in the Cultural Politics of Education 31(5), 605-625.

Li, X., 2009. China's regional innovation capacity in transition: An empirical approach. Research Policy 38(2), 338-357.

Liu, J., Zhang, J., Fu, Z., 2017. Tourism eco-efficiency of Chinese coastal cities–Analysis based on the DEA-Tobit model. Ocean & Coastal Management 148, 164-170.

Lo, S.C.S., 2010. Scientific linkage of science research and technology development: a case of genetic engineering research. Scientometrics 82(1), 109-120.

Lubienski, S.T., Ganley, C.M., Crane, C.C., et al., 2013. Girls' and Boys' Mathematics Achievement, Affect, and Experiences: Findings from ECLS-K. Journal for Research in Mathematics Education 44(4), 634-645.

Mcbrier, D.B., 2003. Gender and Career Dynamics within a Segmented Professional Labor Market: The Case of Law Academia. Social Forces 81(4), 1201-1266.

McWhirter, E.H., 1997. Perceived barriers to education and career: Ethnic and gender differences. Journal of vocational behavior 50(1), 124-140.

Nomaguchi, K.M., 2009. Change in Work-Family Conflict Among Employed Parents Between 1977 and 1997. Journal of Marriage & Family 71(1), 15–32.

Pinch, T.J., Bijker, W.E., 1984. The Social Construction of Facts and Artefacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other. Social Studies of Science 14(3), 399-441.

Romer, P.M., 1986. Increasing Returns and Long-Run Growth. Journal of Political Economy 94(5), 1002-1037.

Ruigrok, A., SalimiKhorshidi, G., Lai, M., BaronCohen, S., Lombardo, M., Tait, R., Suckling, J., 2014. A meta-analysis of sex differences in human brain structure. Neuroscience and biobehavioral reviews 39(100), 34-50.

Schilling, M.A., Phelps, C.C., 2007. Interfirm collaboration networks: The impact of large-scale network structure on firm innovation. Management Science 53(7), 1113-1126.

Siegel, D.S., Westhead, P., Wright, M., 2003. Assessing the impact of university science parks on research productivity: exploratory firm-level evidence from the United Kingdom. International Journal of Industrial Organization 21(9), 1357-1369.

Tavana, M., Shiraz, R.K., Hatami-Marbini, A., 2014. A new chance-constrained DEA model with birandom input and output data. Journal of the operational research society 65(12), 1824-1839.

Twenge, J.M., Campbell, W.K., 2001. Age and birth cohort diGerences in self-esteem: A cross-temporal meta-analysis. Personality & Social Psychology Review 5(5), 321-344.

Wang, E.C., Huang, W., 2007. Relative efficiency of R&D activities: A cross-country study accounting for environmental factors in the DEA approach. Research Policy 36(2), 260-273.

Watcharasriroj, B., Tang, J.C.S., 2004. The effects of size and information technology on hospital efficiency. Journal of High Technology Management Research 15(1), 1-16.

Yang, T., Xin, F., Lei, X., 2015. Gender Differences in the Human Brain Structure and Function: Evidence from Neuroimaging Studies. Advances in Psychological Science(4), 571-581. (In Chinese)

Yue, S.j., 2008. R&D efficiency differences and affecting factor: Across-province analysis using the stochastic frontier approach. Science Research Management 29(5), 173-179. (In Chinese)

Meng, Y. Collaboration patterns and patenting: Exploring gender distinctions. Research Policy, 2016, 45(1), 56-67.

Zhang, Y., Chen, K., Zhu, G., Yam, R.C.M., Guan, J., 2016. Inter-organizational scientific collaborations and policy effects: an ego-network evolutionary perspective of the Chinese Academy of Sciences. Scientometrics 108(3), 1383-1415.

Zhang, Y., Hannum, E., Wang, M., 2008. Gender-Based Employment and Income Differences in Urban China: Considering the Contributions of Marriage and Parenthood. Social Forces 86(4), 1529-1560.