The Effect of Research and Development (R&D) Composition on Labour Productivity Growth among OECD Countries

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Table of Contents

1. Introduction 4

2. Stylized facts of growth model with R&D 7

3. Description of the Data 12

4. Research and Development (R&D) over the business cycle 13

  4.1. The Hodrick-Prescott (HP) filter 13

  4.2. R&D expenditure growth over the business cycle 15

  4.3. The Adjusted R&D expenditure as a ratio of the potential GDP 19

  4.4. Evolution of the R&D expenditure intensities 22

5. Theoretical model and empirical methodology 25

6. Results 29

7. Conclusion 41

Bibliography 43

Figures:

Figure 1. Growth rate of R&D expenditure intensity over the business cycle. OECD countries (1982-2010) 16

Figure 2. Growth rate of R&D expenditure over the business cycle. OECD countries (1982-2010) 17

Figure 3. Impulse responses function of Business and Public R&D expenditure. OECD countries (1981-2010)......18

Figure 4. Growth rate of actual R&D expenditure intensity over the business cycle. OECD countries (1982-2010)......19

Figure 5. Impulse responses function of Business and Public R&D expenditure. OECD countries (1981-2010)......21

Figure 6. Business R&D expenditure intensity trend in OECD countries (1981-2010)......22

Figure 7. Public R&D expenditure intensity trend in OECD countries (1981-2010)......23

Figure 8. Sigma convergence of business and public R&D intensity among OECD countries (1981-2010) 24

Tables:

Table 1. Description of data...12

Table 2. Correlation matrix between average growth rates for 16 OECD countries (1981-2010) 16

Table 3. Effects of total public R&D and business R&D on labour productivity growth..........32

Table 4.Effects of government R&D and business R&D on labour productivity growth...........33

Table 5. Effects of higher education R&D and business R&D on labour productivity growth...34

Table 6. Effects of actual R&D expenditure on labour productivity growth using FGLS.........36

Table 7. Effects of various R&D expenditure intensity measures on labour productivity growth over 1981-2000 using FGLS...39

Table 8. Effects of various R&D expenditure intensity measures on labour productivity growth results of Acharya and Coulombe (2006) using FGLS 40

1. Introduction

Technological progress contributes in a crucial way to economic growth, especially in the developed countries. Therefore a thorough analysis of cross country income disparities and the dynamics of economic growth requires knowledge of the endogenous growth models in which "technology choices and technological progress are endogenized" (Acemoglu (2007, ch.11, p.505)).

Based on Barro and Sala-i-Martin (1995), one straightforward approach of the endogenous growth models was the AK model. This model relaxes the assumption of diminishing returns to capital for a broader range of capital, including human capital as well as physical capital. Another approach applied in the endogenous growth literature to eliminate the assumption of diminishing returns is the one used in the learning-by-doing model. This model, pioneered by Arrow (1962), assumes that the level of the producer's experience has a positive effect on the productivity of a firm. Moreover, as knowledge is a non-rival good, there is also a spill-over effect of knowledge gained by one producer on the productivity growth rate of all other producers. The learning-by-doing model introduces the spill-over effect of knowledge as an engine of economic growth.

A significant development in the evolution of the endogenous growth models was the incorporation of the Research and Development (R&D) sector into the model. Although pioneered by Romer (1990), different versions of the endogenous growth models were later developed by Grossman and Helpman (1991), and Aghion and Howitt (1992). In these models, the R&D sector is the generator of knowledge, which is added to the knowledge stock of the economy. As Romer (1990) states, due to the non-excludability of knowledge, the full stock of knowledge is used as an input in the production functions of both final goods and the R&D sector. Romer (1990) further argues that the R&D activities result in technological innovation which eventually increases the productivity of the goods sector.

In order to evaluate the effect of R&D expenditure on the economic growth, Acharya and Coulombe (2006) distinguish three different measures of R&D expenditure, namely business, public and foreign R&D. The public R&D expenditure is further classified into three measures, i.e. the government R&D expenditure, higher education expenditure and the sum of the two. Moreover, Acharya and Coulombe (2006) use a time-series and cross-section (TSCS) empirical model of annual data from 1981 to 2000 for 16 member countries of the Organization for

Economic Co-operation and Development (OECD).[1] Findings from Acharya and Coulombe (2006) indicate that the effect of business R&D on labour productivity growth is positive and significant. Among the public R&D measures, only higher education expenditure is found to have a positive effect on the labour productivity growth in the long run.

This major paper replicates the model used in Acharya and Coulombe (2006) and extends its analysis as follows; first, the period of estimation is extended to 1981-2009. This period has been specifically chosen as it includes the economic recession of 2008, which was the largest recession since 1930 for most countries. GDP fluctuations have a direct impact on R&D expenditure intensity, since it is defined as the ratio of R&D expenditure to GDP. Consequently, when GDP contracts in a recession, R&D intensity increases even if the R&D expenditure remains constant. Therefore, to understand the impact of GDP fluctuations on the effectiveness of R&D expenditure, this major paper includes an estimation of the Acharya and Coulombe (2006) model using the "adjusted" R&D expenditure intensities which are less responsive to short run business cycles. The adjusted R&D expenditure intensities are defined as the ratio of R&D expenditure to potential GDP which is estimated using the Hodrick and Prescott (HP) filter. Finally, in order to better control for short-run fluctuations in GDP, it is important to analyze the cyclicality of the R&D expenditure. Thus, the behavior of the R&D expenditure over the business cycle is taken into account in this major paper.

More specifically, the paper will aim to answer the following questions:
How does the R&D expenditure respond to the business cycle? Which type of R&D expenditure (public, private and foreign R&D) has the most significant impact on labour productivity growth among the OECD countries? Which component of the public R&D expenditure (government intramural R&D and higher education R&D) has the most pronounced effect on labour productivity growth? Based on regression analysis, how has the financial crisis of 2008 affected the effectiveness of R&D expenditure intensity?

Following the Acharya and Coulombe (2006)'s approach, this major paper tries to answer the aforementioned questions by employing the time series and cross section (TSCS) model of annual data from 1981 to 2009 to the same countries as those analyzed in Acharya and Coulombe (2006). The empirical analysis is divided into two parts. In part one, the evolution of

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[1] The countries included in the study are Australia, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, Norway, Spain, Sweden, the United Kingdom, and the United States

various R&D expenditures over the business cycle is investigated. To better understand the cyclicality of the R&D expenditure intensities, the impulse response functions are generated.

In part two, the Acharya and Coulombe (2006)'s model is estimated for three different sample specifications. First, the model is estimated for the period of 1981-2009 using the same standard definition of R&D expenditure intensity as the one used in Acharya and Coulombe (2006). Second, the adjusted R&D expenditure data is applied to the model for the same time period. Finally, the model is estimated a third time for the period of 1981-2000 in order to compare the results with those of Acharya and Coulombe (2006) and also to show the impact of the economic recession of 2008 on the effectiveness of different measures of R&D expenditure.

This major paper concludes that among all R&D expenditure intensity indicators, only the business R&D component has a positive and significant effect on the labour productivity growth. Estimation results for the period of 1981 to 2000 and comparing results with those of Acharya and Coulombe (2006) illustrate that the financial crisis of 2008 had a measurable impact on the effectiveness of the higher education R&D expenditure intensity. Estimation results using the adjusted R&D expenditure intensities indicate that only the adjusted higher education has a positive and significant effect on labour productivity growth. Furthermore, Acharya and Coulombe (2006) introduce the GDP gap as a control variable for the business cycle. This cyclical component was significant with the expected sign. Analysis reveals that using the adjusted data, the GDP gap becomes insignificant.

The paper is organized as follows: the stylized facts of growth model with R&D are developed in section 2. In section 3, the data and data sources are described briefly. The behavior of R&D expenditure intensity over the business cycle is investigated in section 4. The theoretical model and the empirical methodology are developed in section 5. Next, the estimation results are reported in sections 6. Finally, section 7 presents the conclusion of the analysis.

2. Stylized facts of growth model with R&D

During the 1980-1990 decade, most growth economists agreed that the neo-classical growth model without technological change should be improved in order to better explain the determinants of long-run growth. Barro and Sala-i-Martin (1995) argues that the neo-classical growth model predicts that in the long-run all economies will converge to their individual steady states. The main reason for this prediction is the existence of diminishing returns to capital. Therefore one way to remove this limitation in the neo-classical model is to ignore this assumption in the long-run. According to Barro and Sala-i-Martin (2003), the absence of diminishing returns to capital was applied for the first time in the AK model. The AK model broadens the range of capital to include human capital, as well as physical capital. Thus the assumption of diminishing returns does not hold for this broader range of capital. As stated by Barro and Sala-i-Martin (2003), because in the basic AK model the marginal and average products of capital are always constant, this model does not predict conditional convergence. However, in the light of Barro and Sala-i-Martin (2004)'s analysis, based on the idea which is introduced by Jones and Manuelli (1990), it is possible to have conditional convergence as long as the assumption of constant returns to capital is also held.

Barro and Sala-i-Martin (2003) argue that there are other methods which have been used to eliminate diminishing returns. The learning-by-doing model is another approach which was introduced by Arrow (1962) and mainly developed by Romer (1986). According to Barro and Sala-i-Martin (2003), the learning-by-doing model assumes that the level of the producer's experience has an influence on productivity. There is also a spill-over effect of experience gained by one firm on the productivity of other firms in the competitive market. Therefore the level of technology is increased by "a larger economy-wide capital stock". Under these conditions, there is not only lack of evidence of the diminishing returns, but the existence of increasing returns is also viable possibility. (Barro and Sala-i-Martin (2003, p.65))

Barro and Sala-i-Martin (2003) explains that another way to neglect the assumption of diminishing returns is to view the technological changes as generation of new ideas. The "endogenous growth model" pioneered by Paul Romer (1990), introduces the Research and Development (R&D) sector in order to model technological innovation. As stated in Barro and Sala-i-Martin (2003), the growth model with R&D sector was mainly developed by Grossman and Helpman (1991), and Aghion and Howitt (1992). In this model, the R&D sector is explicitly introduced as the key indicator for the technological innovation to capture the production of new technologies. As presented in David Romer (2012), there are two sectors in the economy, a goods producing sector and an R&D sector. R&D is used as a factor of production in the production function of goods. This sector generates a flow of knowledge that adds to the economy's stock of knowledge (Romer (2012, ch3, p.103)).

Romer (2012) assumes that the Cobb-Douglas production function includes four variables: labour (*L*), capital (*K*), technology (*A*) and output (*Y*). The model is set in continuous time. The fraction α_L of the labour and α_K of the capital stock is used in the R&D sector. According to Romer (2012), because of the non-excludability property of knowledge, both the production and the R&D sector use the full stock of knowledge. Based on this information, Romer (2012) formulates the production function as follows:[2]

$$Y(t) = \left[(1-\alpha_K)K(t)\right]^{\alpha}\left[A(t)(1-\alpha_L)L(t)\right]^{1-\alpha}, 0 \prec \alpha \prec 1$$

The above equation indicates the presence of constant returns with respect to capital and labour. Romer (2012) considers the production of new ideas in the R&D sector to be dependent on the amount of capital, labour and the level of technology in the economy and summarizes this relationship in the equation below:

$$\dot{A}(t) = G(\alpha_K K(t), \alpha_L L(t), A(t))$$

Romer (2012) discusses that the production of new ideas in the R&D sector has a Cobb-Douglas functional form and formulates $\dot{A}(t)$ as follows:

$$\dot{A}(t) = B\left[\alpha_K K(t)\right]^{\beta}\left[\alpha_L L(t)\right]^{\gamma} A(t)^{\theta}, B \succ 0, \beta \geq 0, \gamma \geq 0$$

Romer (2012) also indicates that there is no necessity to have constant return in the production of new ideas in the R&D sector. At the same time, there is a possibility of having increasing returns with respect to labour and capital. Romer (2012) argues that there is no

[2] This section borrows heavily from David Romer (2012).

restriction on the impact of the knowledge stock ($A(t)$) on the knowledge generation, therefore θ can assume any value. As θ increases, the impact of the knowledge stock on the growth rate of technological innovation will increase. For simplicity, Romer (2012) assumes a model without capital in order to investigate the dynamics of knowledge accumulation. Thus it formulates the production function to include only technological innovation and labour, as shown in the equation below:

$$Y(t) = A(t)(1 - a_L)L(t)$$

$$\dot{A}(t) = B\left[a_L L(t)\right]^{\gamma} A(t)^{\theta}$$

As long as the population growth rate (n) is exogenous, the output per worker is a fraction of the knowledge stock. Therefore the growth rate of output per worker is equal to the growth rate of knowledge accumulation (Romer (2012, ch.3, p.104)). Hence to investigate the productivity growth, Romer (2012) analyses the dynamics of knowledge accumulation, which is derived from the growth rate of knowledge accumulation g_A:

$$g_A(t) = \frac{\dot{A}(t)}{A(t)} = B a_L{}^{\gamma} L(t)^{\gamma} A(t)^{\theta-1}$$

Romer (2012) further argues that since B and a_L are constant and the population growth rate is exogenous, the growth rate of g_A is defined by the equation below:

$$\dot{g}_A(t) = \left[\gamma n + (\theta - 1) g_A(t)\right] g_A(t)$$

In the steady state, the $\dot{g}_A(t)$ is zero. Therefore the growth rate of output per worker (g_A^*), as given by Romer (2012) is represented as:

$$g_A(t) = \frac{\gamma n}{1-\theta} = g_A^*$$

Therefore the dynamics of g_A depend on the value of θ. As stated by Romer (2012), there could be three different scenarios based on the value of θ ($\theta < 1$, $\theta = 1$, $\theta > 1$). The scope of this major paper only includes analysis of the first case ($\theta < 1$) as this is the case applied in the empirical framework.

$\theta < 1$ means that as the stock of knowledge increases, the generation of new ideas increases by a lesser degree. In this case g_A^* is an increasing function of population growth rate (n) which means that the growth rate of output per worker will increase as population growth rate increases. Romer (2012) argues that this conclusion is acceptable when the model is a "worldwide economic growth" model. Based on his argument, in the worldwide economic growth model, as the population growth rate increases, the possibility of new discoveries will also increase. Thus, the worldwide level of technology (A) will increase as well. Higher level of (A) leads to higher growth rate of knowledge accumulation (g_A) which would eventually lead to a higher level of output per worker growth rate. As Romer (2012) mentions, when $\theta < 1$, increase in the fraction of labour employed in the R&D sector (a_L) only has a level effect on the path of (A) since the contribution of the knowledge stock in the generation of new knowledge is restricted (Romer (2012, ch.3 , p.106)).

Thus, from the arguments used in Romer (2012), it can be concluded that when the effect of knowledge stock on the growth rate of the knowledge generation is less than one to one, the endogenous growth model with R&D sector displays the property of convergence for a cross-country dataset. In the two other possible scenarios ($\theta = 1$ and $\theta > 1$) the economies witness a continuously increasing output growth rate, ultimately diverging from their balanced growth path. (Romer (2012, ch.3, pp.107-108)).

Since Romer (1990) there have been a considerable number of studies conducted which examine the relationship between R&D expenditure and productivity growth, especially for the developed countries. As Acharya and Coulombe (2006) indicates, there are two alternative approaches which can be used to investigate the relationship between R&D expenditure and the long-run economic growth rate of an economy:

The first approach focuses on the impact of R&D expenditure on the growth rate of labour productivity, pioneered by Nonneman and Vanhoudt (1996). In this approach, the augmented Solow growth model (Mankiw et al., 1992)[3] is used as a foundation and R&D capital is included as an independent variable. Findings of Nonneman and Vanhoudt (1996) indicate that the Solow

[3] Mankiw et al. (1992) develops the Solow growth model by including human capital as an additional explanatory variable in the model, called the augmented Solow growth model.

growth model with the R&D variable can explain income disparities better than the augmented Solow model. As Nonneman and Vanhoudt (1996) argues, the effect of R&D capital on the labour productivity growth rate is positive and significant at the 10% level. After the Nonneman and Vanhoudt (1996)'s analysis, the positive relationship of the R&D expenditure and labour productivity was also confirmed by Keller and Poutvaara (2003), OECD (2003) and Acharya and Coulombe (2006).

The second approach estimates the impact of R&D expenditure on the total factor productivity (TFP). Several studies such as Frantzen (2000) and Griffith et al. (2004) confirm a positive relationship between R&D expenditure and TFP. Furthermore, Scherer (1982), Griliches and Lichtenberg (1984), Aghion and Howitt (1992), and Zachariadis (2003) argue that there is strong evidence of a positive correlation between R&D investment and TFP growth in the U.S. economy. As stated by Coe and Helpman (1995), Griffith et al. (2004), and Zachariadis (2003), this approach is very useful in estimating the effect of R&D spillover on TFP growth rate of developing countries.

Following Acharya and Coulombe (2006), this major paper employs the first approach due to the following three reasons. First, contrary to labour productivity convergence in cross-country studies, there is no evidence of TFP convergence. Second, as long as there is a possibility of a significant measurement error for computing TFP even for a single country, it would not be possible to accurately compute the cross-country TFP growth rate. The last and most important reason being, as Acharya and Coulombe (2006) argue in the light of seminal work by Hall (1988), that in the case of non-constant return and imperfect competition, TFP is a biased measure of the unobserved actual productivity growth. As stated before, Romer (2012) argues that in the endogenous growth model with R&D sector there is a possibility of increasing returns and also imperfect competition. Hence labour productivity is a more reliable indicator than TFP to use in a cross country study. (Acharya and Coulombe (2006, p.6))

3. Description of the Data

Following Acharya and Coulombe (2006), most of the data used in this major paper is extracted from the OECD database. The Penn World Table (PWT) (Alan Heston et al., 2002) is used to obtain data for the labour productivity, population growth and the investment intensity indicators.

Table 1 presents a detailed description of the data used in this major paper.

Table 1. Description of Data

Indicator	Database	Variable
Real GDP chain per worker at 2005 prices	PWT	Labour productivity
Quarterly real GDP volume at 2005 prices and constant PPP	OECD Economic Outlook Quarterly database	Cyclical component
R&D expenditure series in 2005 prices and constant PPP	OECD	R&D expenditure intensities
Investment intensity indicators	PWT	Investment
Population growth	PWT	Population growth
International import	OECD	Weights of foreign R&D
Real GDP volume at 2005 prices and constant PPP	OECD	Weights of Foreign R&D

It is important to mention that since the R&D data was unavailable for a few countries, the average of one year before and one year after has been used in place of the missing values. In addition, for those cases in which data was missing for two consecutive years, the average of the next and previous closest years is applied. This is not a big problem since it is just for a few countries and a few years.

It is also worthwhile to know that the PWT database is updated till 2009 whereas the OECD database is updated till 2010. In the following section, in order to better illustrate the evolution of the R&D indicators over the financial crisis of 2008, the investigated period is up to 2010 while due to the lack of data for the regression section the estimation period is up to 2009.

4. Research and Development (R&D) over the business cycle

As observed during the economic recession of 2008-2009, the R&D expenditure displayed a less elastic behaviour than other economic variables. Most OECD countries experienced a rapid drop in their GDP in 2008. Since R&D expenditure intensity is measured as a ratio of R&D expenditure to GDP, these OECD countries witnessed an increase in their R&D expenditure intensities which was a consequence of the R&D expenditure falling by less than the GDP. Census results show that gross domestic R&D expenditure intensity (GERD) among the OECD countries increased from 2.3 in 2008 to 2.4 in 2009, whereas the growth rate of GERD decreased from 3.1% in 2008 to 2.1% in 2009. However, the effect of the financial crisis on R&D expenditure may become more pronounced after a one to two years lag.

As a key factor of economic growth, it is important to investigate the behaviour of R&D expenditure over the business cycle. Subsequently, in section 3.1, first the GDP gap is introduced, and then the Hodrick-Prescott (HP) filter as a method of estimation for potential GDP is studied. In section 3.2, the R&D expenditure's behaviour and its cyclicality over the business cycle is investigated. For a deeper analysis, the evolution of R&D expenditure intensity through sigma convergence is considered is the last section.

4.1. The Hodrick-Prescott (HP) filter

The output gap is defined as the difference between actual and potential GDP as a percentage of potential GDP. Computing the GDP gap is always subject to many problems due to the unobservability of the potential GDP from the data. Among the available methods for the estimation of potential GDP, the Hodrick-Prescott filter (HP) pioneered by Hodrick and Prescott (1997), is used in this major paper. The idea behind this method is to decompose the time series into two parts, separating the cyclical component from the trend. As stated by St-Amant and van Norden (1997), doing so yields a smooth presentation of time series. In this case, suppose Y_t denotes the logarithm of a time series variable. As stated by St-Amant and van Norden (1997), the HP filter breaks down this time series into a cyclical component and a growth component as shown below:

$$Y_t = Y_t^g + Y_t^c$$

In the light of St-Amant and van Norden (1997)'s analysis, for a given positive value of λ, HP filter suggests a trend component Y_t^c which solves the following minimization problem:

$$\min \sum_{t=1}^{T} \left[\left(Y_t - Y_t^g\right)^2 + \lambda \left[\left(Y_{t+1}^g - Y_t^g\right) - \left(Y_t^g - Y_{t-1}^g\right) \right]^2 \right]$$

Applying the HP filter according to the above equation, the variance of the cyclical component is minimized subject to a penalty for the variation in the second difference of growth component. Hodrick and Prescott (1997) argues that the adjustment of the smoothness is dependent on the value of λ. The larger the value of λ, the smoother the growth component will be due to the higher value of the penalty. As Hodrick and Prescott (1997) suggests, a value of 1600 for λ is sensible for quarterly data.

It is worthwhile to note that the main problem when using the HP filter to estimate actual GDP is the unreliability of this estimation at the end and beginning of the sample. As stated by St-Amant and van Norden (1997), in the presence of a temporary shock, the HP filter is "reluctant" to change the trend with any significance, since the HP filter method tends to raise the trend before shock and lowering it afterwards. This property implies that the HP filter will be more sensitive to shocks at the end and beginning of the sample than in mid-sample. (St-Amant and van Norden (1997, p.14))

To overcome this problem, this major paper follows the approach outlined in Acharya and Coulombe (2006). For the raw data of real GDP, the GDP volume at 2005 constant PPP is used, which is derived from the OECD Economic Outlook Quarterly database for a sample period of 46 years (1965Q1 to 2011Q4). The measure for the GDP gap is obtained from the quarterly real GDP data using the HP filter with a smoothing parameter (λ) of 1600.

4.2. R&D expenditure growth over the business cycle

In order to fully appreciate the importance of R&D as an engine of economic growth, various measures of R&D expenditure can be studied. According to the OECD (2002),[4] gross domestic expenditure on R&D (GERD) refers to "total intramural expenditure on R&D performed on the national territory during a given period." The GERD is divided into four sectors: business enterprises (BERD), government (GOVERD), higher education (HERD) and private non-profit. (*Frascati Manual* (2002, ch.6, p.121))

Among these four sectors, previous studies generally conclude that the business R&D expenditure has a positive and significant effect on the productivity growth rate in the long-run. The findings of Acharya and Coulombe (2006) suggest that an OECD country which has invested 10% above OECD average into the business R&D sector experiences higher labour productivity growth ranging from 2.4% to 5% in the long-run.

Conversely, the effect of public R&D expenditure (which could be measured as either government R&D expenditure, higher education R&D expenditure or the sum of the two) on labour productivity is not strongly significant. In this case, Acharya and Coulombe (2006) show that investment in public R&D has limited returns and only higher education expenditure has a positive effect on the labour productivity growth rate. A study completed by the OECD (2003) reported a negative and significant effect for the sum of the government and the higher education R&D expenditures on labour productivity growth rate; however, the significance of the results is due to the estimation of TSCS data by the SUR method. According to Beck and Katz (1995), estimation of TSCS data with SUR estimators leads to extreme overconfidence. This issue is further discussed in section 5.

A simple analysis of correlation between the average annual growth rates (1981-2010) of R&D expenditure and GDP is shown in Table 1. The average GDP growth rate and the business R&D expenditure display a modest positive correlation, while the correlation between GDP growth rate and public R&D is positive and smaller than the business R&D.

[4] The OECD (2002) prepared a document which is named *Frascati Manual. Frascati Manual* sets the methodology for collecting statistics about R&D.

Table 1. Correlation matrix between average growth rates for 16 OECD countries (1982-2010)

	Business R&D	Public R&D
GDP growth	0.64	0.31
Public R&D	0.31	1
Business R&D	1	0.34

The growth rate of the business and public R&D expenditure for OECD countries over the business cycle is also reported in Figure 1. As illustrated, growth rate of business R&D fluctuates procyclicaly, with the size of the fluctuations being larger than those for GDP while the public R&D growth rate seems countercyclical. It is important to note that in the empirical part of this major paper, the business and public R&D expenditure intensities are used as control variables. In this context realizing the cyclicality of these expenditure intensities is more complicated because both R&D expenditure (as a numerator) and GDP (as a denominator) change during the business cycle.

Figure 1. Annual growth rate of R&D expenditure over the business cycle. OECD countries (1982- 2010)

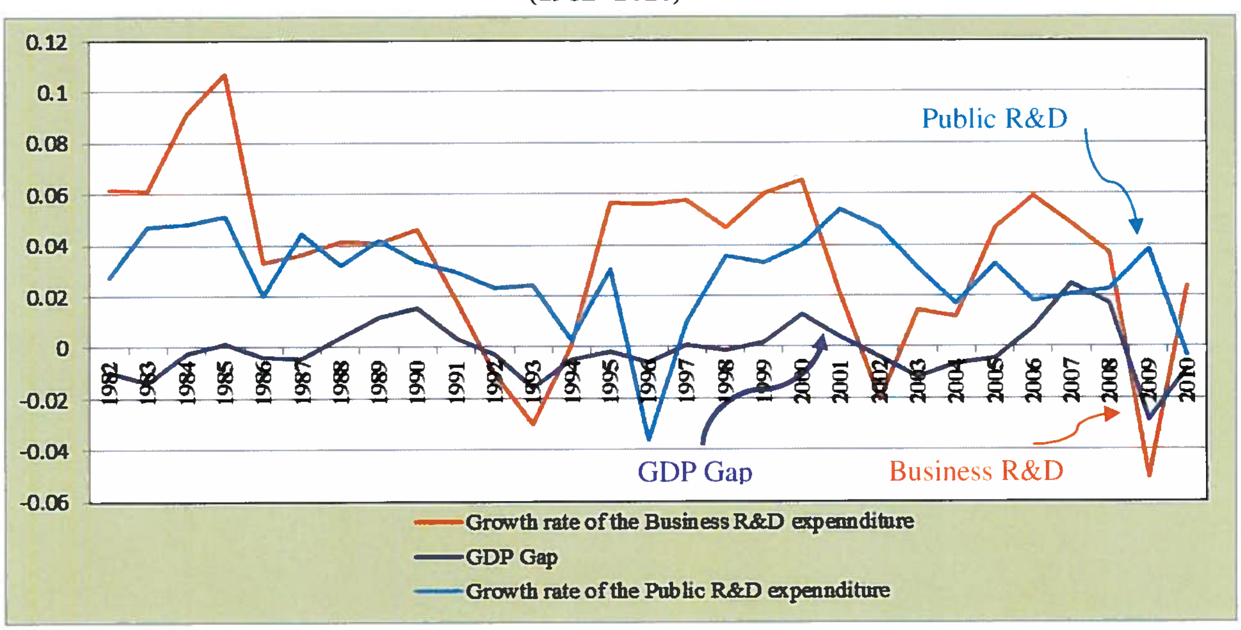
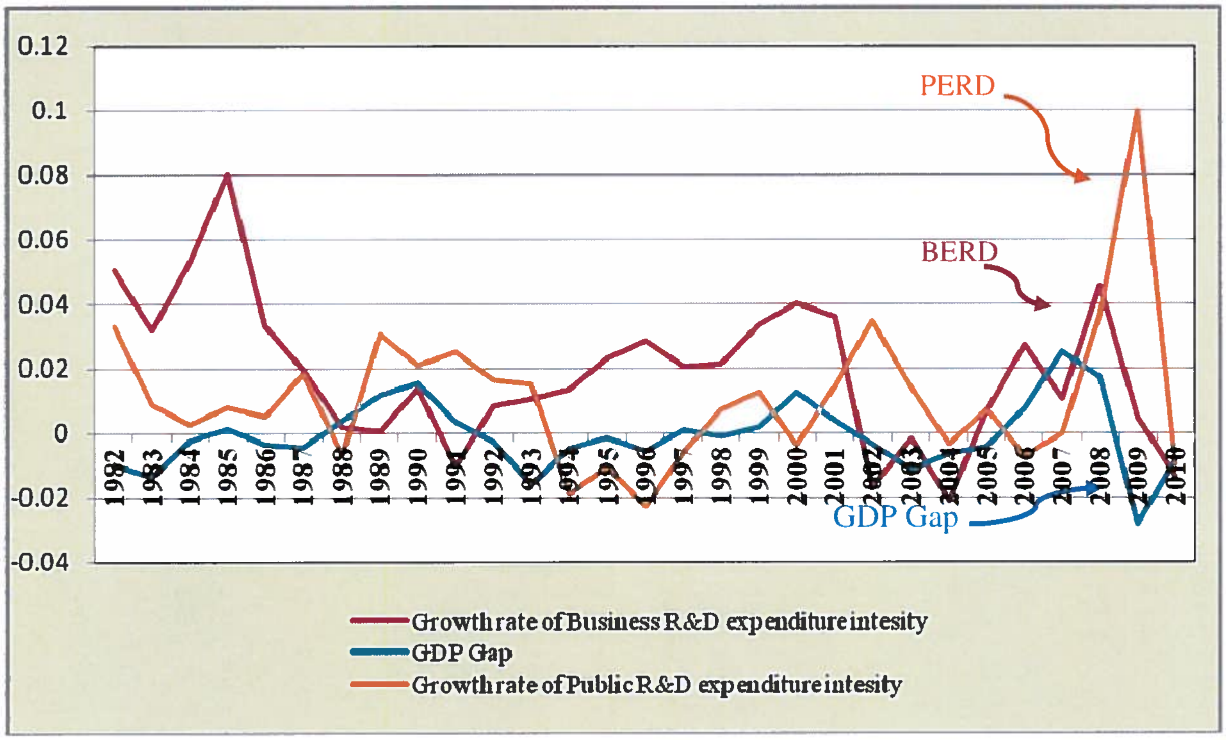


Figure 2 shows that the business R&D expenditure intensity (BERD) tends to follow the business cycle (GDP gap) with a time lag of one to two years. The growth rate of business R&D intensity commonly fluctuates in a similar fashion to the GDP, but with larger fluctuations. In contrast, the public R&D expenditure intensity (PERD) shows smaller and usually countercyclical fluctuations.

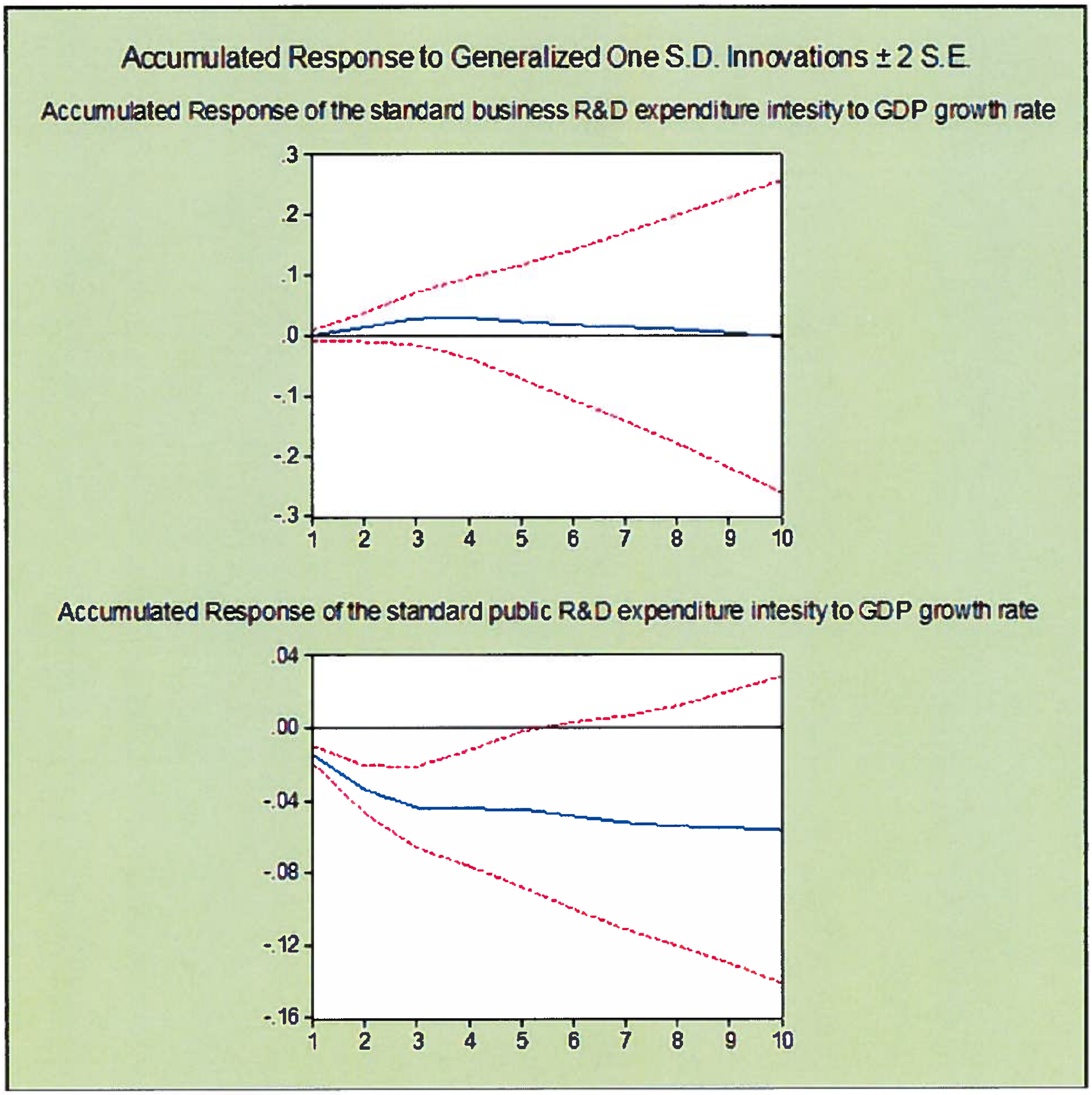
Figure 2. Annual growth rate of Business R&D and Public R&D expenditure intensity over business cycle. OECD countries (1982-2010)



In order to study the trend of the R&D expenditure intensity in greater depth, the impulse response functions of the business and the public R&D expenditure intensities are considered. To generate the impulse response functions this major paper computes the accumulated responses of business and public R&D expenditure intensity. The functions are specified in the framework of unrestricted VAR. The average growth rate of GDP is considered as an endogenous variable and R&D expenditure intensities, openness, investment as a ratio of GDP and population growth rate are chosen as exogenous variables.

Figure 3 shows the change in the path of these two indicators in response to a one percent standard deviation positive shock to the OECD average growth rate of GDP for the period of 1981 to 2010. The numbers on the horizontal axis represent the years elapsed since the shock, which occurs in the first year. As observed, the shock causes the business R&D intensity, represented by the blue line, to increase to a maximum level in the third year, after which it slowly diminishes and the effect of the shock is completely gone in the tenth year. In contrast, the shock causes public R&D intensity to fall rapidly till the third year, after which the decline slows but the level of public R&D intensity remains low.

Figure 3. Impulse responses function of the standard Business and Public R&D expenditure. OECD countries (1982-2010)

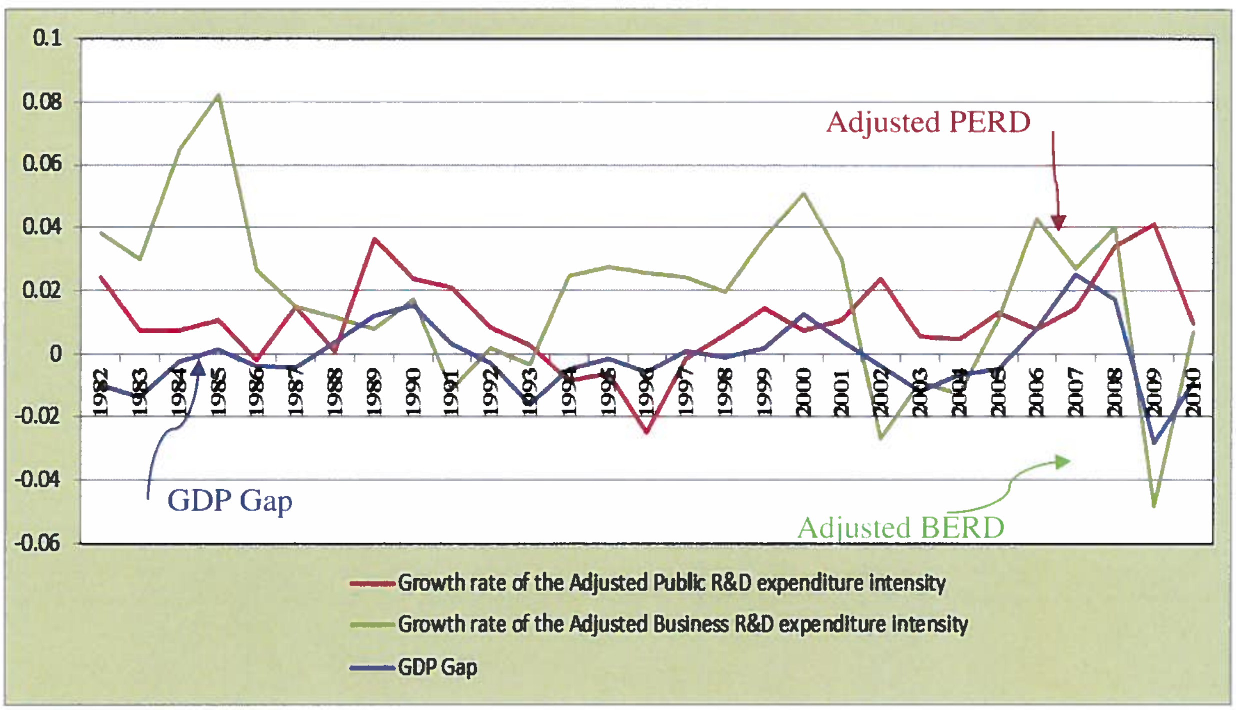


4.3. The Adjusted R&D expenditure as a ratio of the potential GDP

In order to compute the net effect of the economic crisis of 2008 on R&D expenditure, this major paper proposes the use of the adjusted R&D expenditure intensity which is defined as the ratio of the real R&D expenditure to the potential GDP. By doing so, the cyclicality of the R&D expenditure can be studied more accurately since the potential GDP is a smoother presentation of the actual GDP.

Figure 4 shows the growth rate of the adjusted R&D expenditure over the GDP gap. The cyclicality of the business and the public R&D can be confirmed by analyzing this figure. The adjusted business R&D expenditure seems procyclical and it fluctuates more than the GDP gap while the adjusted public R&D seems countercyclical.

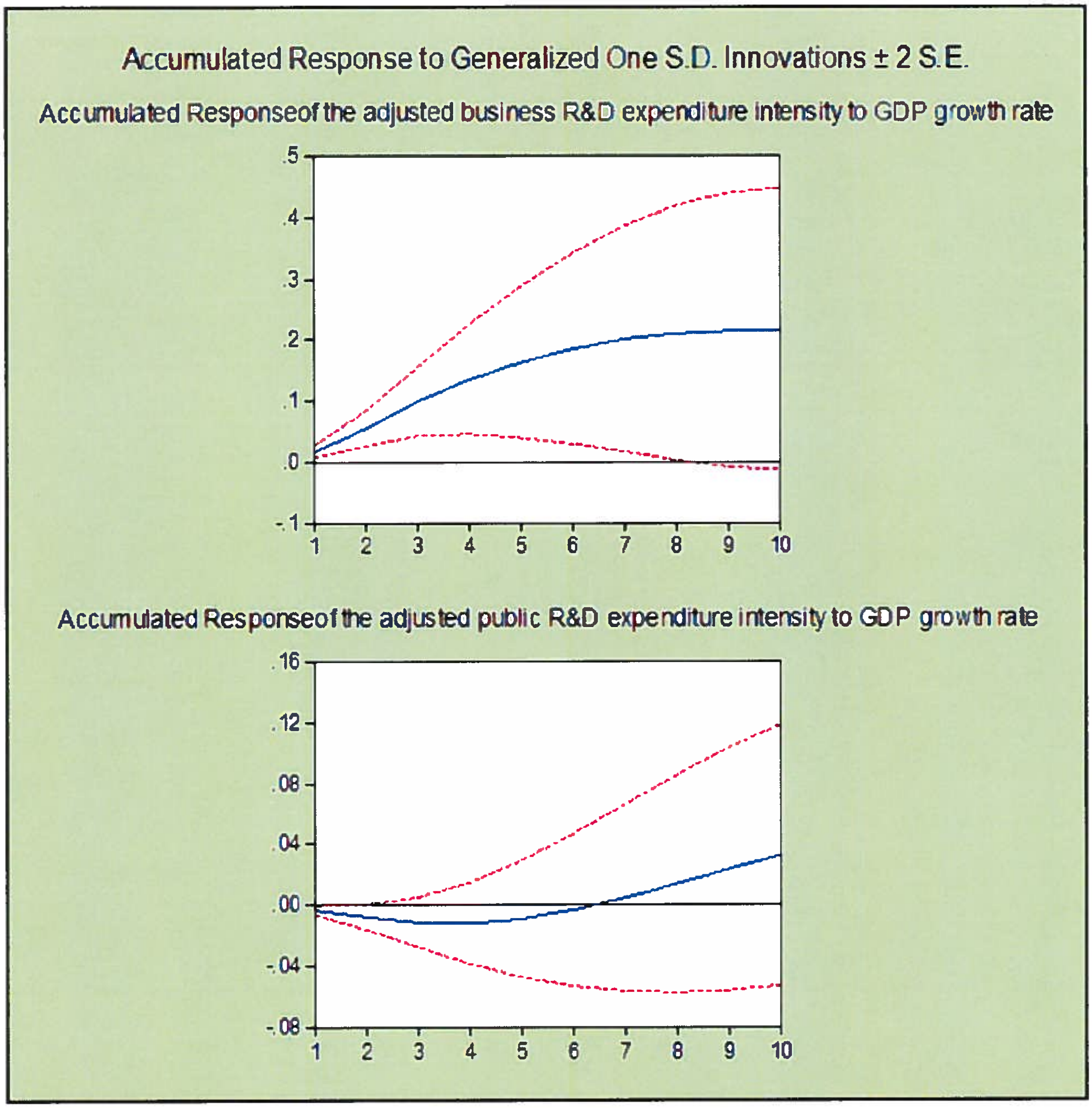
Figure 4. Annual growth rate of the Adjusted R&D expenditure intensity over the business cycle. OECD countries (1982-2010)



The impulse response functions of the adjusted business and public R&D expenditures are reported in Figure 5. As illustrated, the adjusted business R&D intensity increases in response to a one percent positive shock to the GDP growth while the adjusted public R&D intensity decreases in response to the same shock. Consequently, the decline in the GDP due to the financial crisis of 2008 caused a greater drop in the business R&D expenditure, compared to the public R&D expenditure. As a result, the business R&D expenditure intensity is observed to fluctuate procyclically while that for public R&D fluctuates countercyclically.

A comparison between the impulse response functions for the standard and the adjusted R&D expenditure intensities indicates that in response to a positive GDP shock, the adjusted business R&D expenditure intensity increases more than the standard R&D expenditure intensity. Since the potential GDP is a smoother presentation of the actual GDP, the response of the adjusted business R&D expenditure intensity as a ratio of the potential GDP is more pronounced than the response of the standard business R&D expenditure intensity. This is mostly because of the procyclicallity of the business R&D expenditure. In other words, for the business R&D expenditure intensity, both the numerator and the denominator move in the same direction. Thus, if the fluctuation in the denominator is smaller relative to the numerator, the response of the ratio will be larger. Contrarily, due to the counter cyclicality of the public R&D expenditure, the adjusted public R&D expenditure intensity decreases to a lesser degree relative to the standard R&D expenditure intensity in response to a positive GDP shock.

Figure 5. Impulse responses function of the Adjusted Business and Public R&D expenditure. OECD countries (1982-2010)



4.4. Evolution of the R&D expenditure intensities

In order to assess the impact of the economic recession of 2008 on the R&D expenditure, the trend of the business and public R&D expenditures and also the evolution of these two indicators through the sigma convergence analysis for 16 OECD countries from 1981 to 2010 are analyzed in this section.

Figure 6. Annual business R&D expenditure intensities among OECD countries (1981-2010)

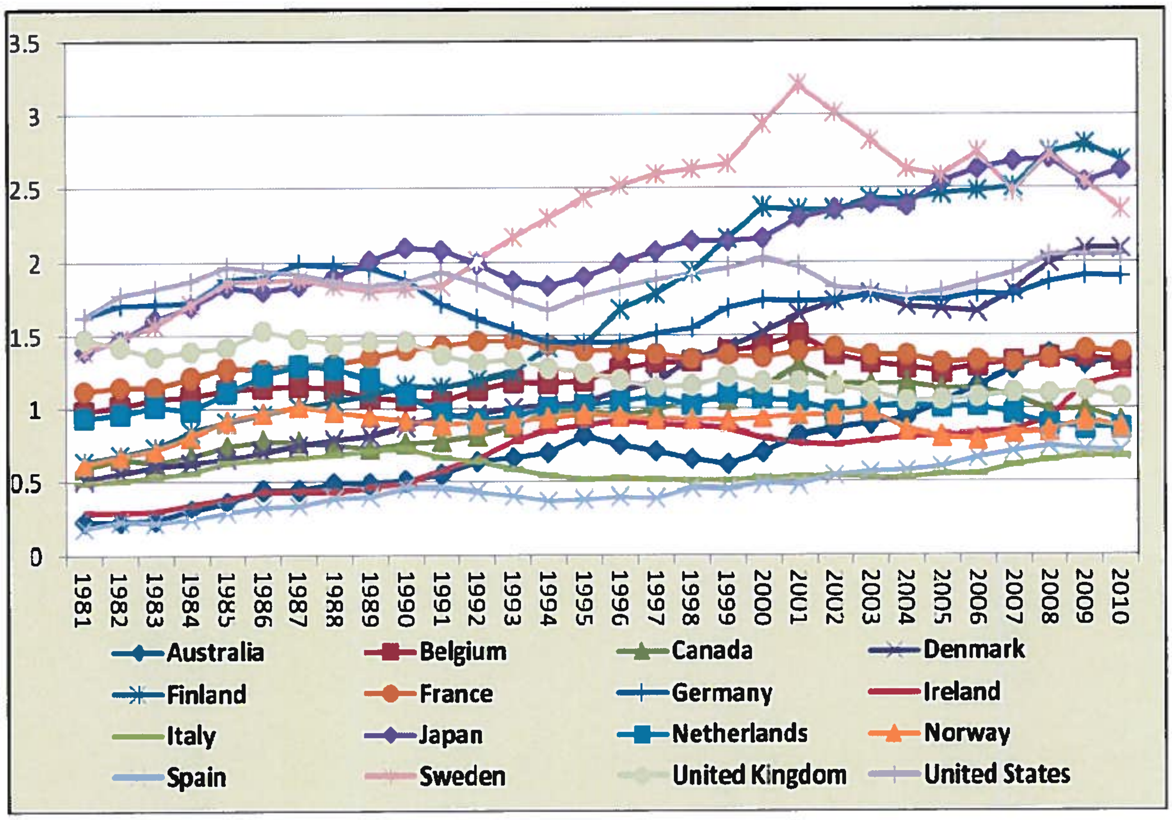


Figure 6 shows that due to the recent financial crisis, business R&D expenditure intensity decreased in most of the OECD countries. Thus, the growth rate of average business R&D is seen to have fallen from 4.8% in 2007 to 3.6% in 2008 and -5.1% in 2009. It is also worth noting that in 2010, due to the global economic recovery, the average growth rate of business R&D increased to 2.4%.

Figure 7. Annual public R&D expenditure intensity in OECD countries (1981-2010)

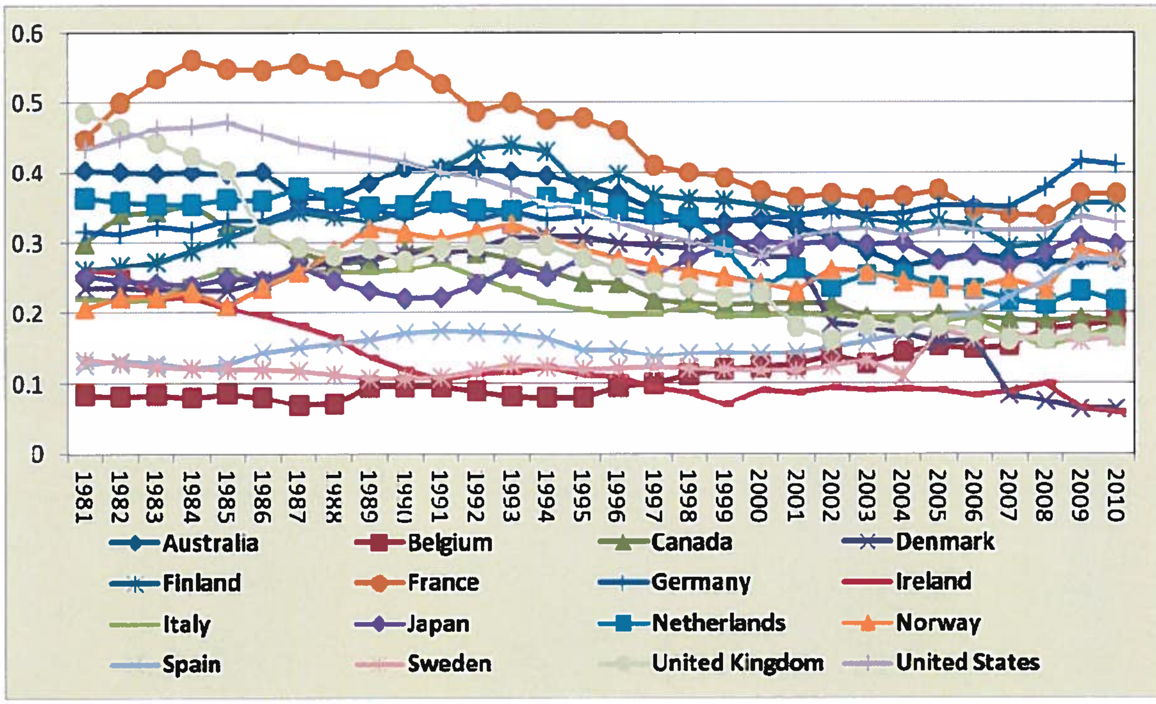


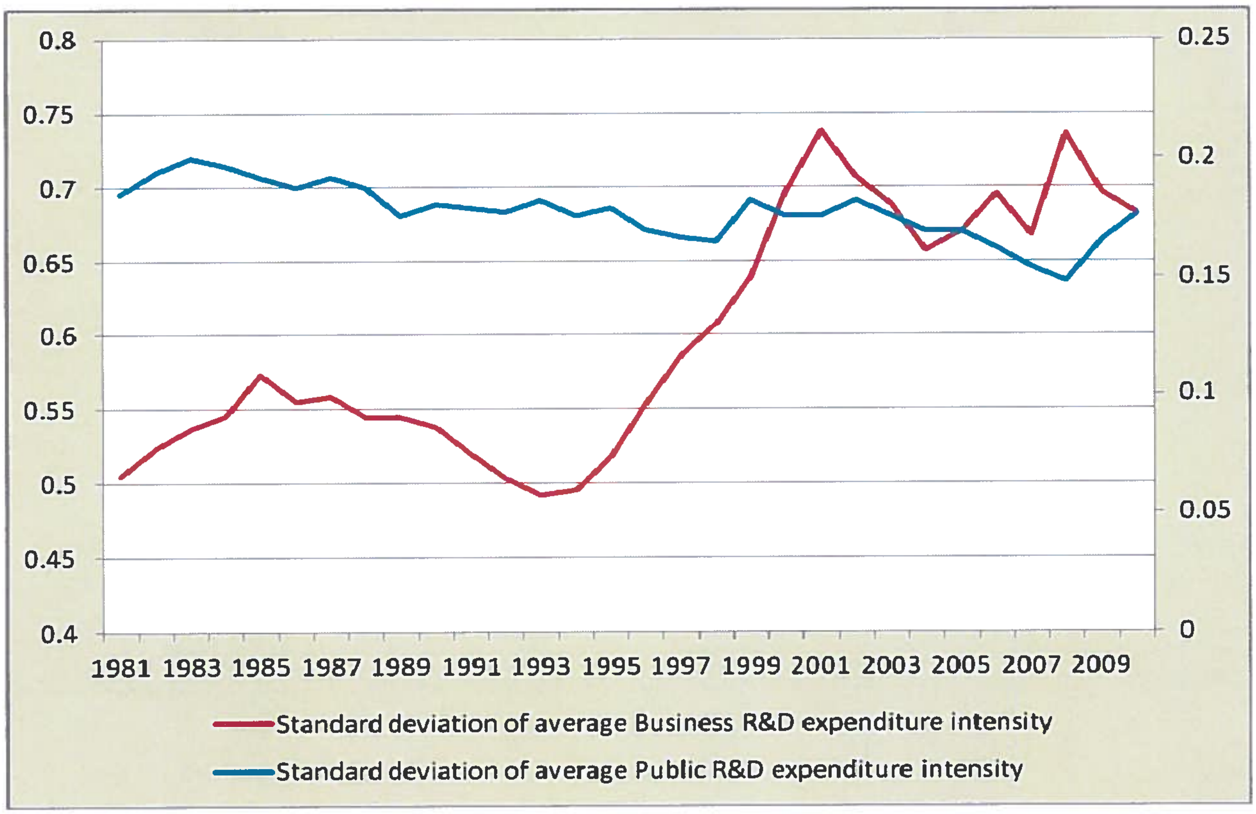
Figure 7 displays the counter cyclicality of public R&D expenditure intensities, showing that in 2009 public R&D intensity increased for most OECD countries. The growth rate of average public R&D expenditure intensity increased from 2.0% in 2007 to 2.3% in 2008 and 3.8% in 2009. As the global economy recovered, the growth rate of average public R&D expenditure intensity decreased to -0.3% in 2010.

Observing the R&D expenditure intensity at the end of 2010 raises the question of whether the distribution of these indicators converged, diverged or remained intact over the last decade. The findings of Martín et al,(2004) reveal that the public R&D spending and patent applications have converged among the OECD countries during the 1990s while the private R&D spending has diverged as a result of an asymmetric expansion during the second half of the 1990s.

Since sigma convergence shows the evolution of the dispersion of R&D expenditure as a percentage of GDP, convergence in the sense of sigma can be claimed if the dispersion of R&D expenditure intensity decreases over time.

The sigma convergence analysis in Figure 8 illustrates that between 1981 and 2008, dispersion of the public R&D intensity has decreased, which implies that sigma convergence exists over this period. After 2008, the dispersion of public R&D intensity increased under the influence of the budget reduction in the countries that are mostly affected by the financial crisis. The evolution of business R&D expenditure dispersion is not as unidirectional. Figure 8 clearly depicts that the dispersion of business R&D increases between 1994 and 2001, while during 2001 and 2004, it falls; meaning sigma convergence for business R&D can be established over the later period. The dispersion is seen to be relatively stable from 2005 till 2007, but is observed to decrease as the financial recession of 2008 sets in.

Figure 8. Sigma convergence of business and public R&D intensity among OECD countries (1981-2010)



5. Theoretical model and empirical methodology

As Nadiri (1993) mentions a Cobb-Douglas production function is usually used to relate the productivity growth to the amount of labour, stock of capital and stock of R&D. In the light of Nadiri (1993) summarizations, the constant return to scale with respect to the labour and capital and very small (almost zero) depreciation rate for the R&D stock are the two crucial assumptions in the most previous studies. (Nadiri (1993, p.9)).

In this major paper, the contribution of R&D expenditure to the labour productivity is estimated in accordance with the neo-classical convergence-growth framework.[5] As stated by Acharya and Coulombe (2006), convergence-growth framework suggests that the growth rate of labour productivity ΔY_{it}, (log difference) for country i during period t, is a function of the gap between its steady-state (log) level value at time t (Y^*_{it}) and its initial (log) level value at time $t-1(Y_{it-1})$. The equation formulated by Barro and Sala-i-Martin (1995) is as follows:

$$\Delta Y_{i,t} = -\beta (Y^*_{i,t} - Y_{i,t-1}) \qquad (1)$$

In the neo-classical framework, the estimated β, which is derived from yearly data, is the annual speed of convergence toward the steady-state. As stated by Acharya and Coulombe (2006), to test the convergence property, the growth rate of labour productivity is generally regressed on its initial level and a set of control variables, $Z_{i,t}$ are used as proxies for the steady-state Y^*_{it}. Following Coulombe and Lee (1995) and Islam (1995), with time-series and cross-section (TSCS) technique, equation (1) can be modeled in a two-way Error Correction Model (ECM) with time dummies and fixed effects as shown below:

$$\Delta Y_{i,t} = \beta Y_{i,t-1} + \alpha Z_{i,t} + f_i + \theta_t + u_{i,t} \qquad (2)$$

In this equation, u_{it} is the white noise disturbance which measures the effect of transitory shocks on economy i during period t. The fixed effects element, f_i, is used in order to capture the unobserved time-invariant heterogeneity across countries. In the aforementioned formula, Z_{it} is the log of the vector of control variables which includes the R&D variables as well as the other

[5] This section borrows heavily from Acharya and Coulombe (2006).

control variables such as investment ratio, population growth rate and Y_{it} as the log level of output. Based on the neo-classical framework, in the steady-state $\Delta Y_{it}^{*}=0$ and $\beta < 0$, thus Acharya and Coulombe (2006) rewrite the formula as follows:

$$0 = \beta Y^{*} + \gamma Z^{*} + 0$$

This yields the following equation:

$$Y^{*} = -\frac{\gamma}{\beta} Z^{*}$$

Where $-\frac{\gamma}{\beta}$ is the long-run elasticity of productivity with respect to the R&D expenditure.

Following Acharya and Coulombe (2006), reported results in this study stem from different methods of estimation of equation (3), which is adapted from equation (2).

$$\Delta Y_{i,t} = \beta Y_{it\text{-}1} + \alpha_c CC_{it} + \alpha_I I_{it} + \alpha_n N_{it} + \alpha_o OPEN_{it} + \alpha_{br} BR_{it} + \alpha_{pr} PR_{it} + \alpha_{fr} FR_{it} + \gamma_{br} \Delta BR_{it} + \gamma_{pr} \Delta PR_{it} + \gamma_{fr} \Delta FR_{it} + \sigma_g G + f_i + \theta_t + u_{it} \quad (3)$$

It is also notable that all variables are in the logarithm form and Δ indicates the first logarithmic difference. The variables are defined as follows:

CC_{it}	The business cyclical component :GDP gap in percentage
I_{it}	The logarithm of investment share of GDP
N_{it}	The annual population growth rate
$OPEN_{it}$	The logarithm of trade (export plus import) share of GDP
BR_{it}	The logarithm of business R&D expenditure intensity
PR_{it}	The logarithm of public R&D expenditure intensity
FR_{it}	The logarithm of foreign R&D expenditure intensity
G_i	German1991 dummy

Following Acharya and Coulombe (2006), this study distinguishes between the three sources of the R&D expenditure: domestic, foreign and public R&D as well as three alternative measures for the public R&D expenditure, namely the government R&D expenditure (GOVERD), the higher education expenditure (HERD) and the sum of the two (PERD). To compute the foreign R&D, in the light of the Acharya and Coulombe (2006)'s analysis, the indicator used is the one proposed by Coe and Helpman (1995). Coe and Helpman (1995), as pioneers in investigating the relationship between the foreign R&D and TFP growth, introduced the trade flows as transmission mechanisms of foreign R&D. In this study, following Acharya and Coulombe (2006), the foreign R&D expenditure for country *i* in year *t* is calculated as a weighted sum of its imports share from each of the other 15 countries relative to the total imports, divided by the GDP of the trading partner, where the weighting factor is the R&D expenditure of the trading partner. Acharya and Coulombe (2006) calculate foreign R&D expenditure for country *i* in year *t* as follows:

$$r_{it}^{*} = \sum_{j=1, i\neq j}^{15} \frac{1}{Y_{jt}} m_{ij} r_{jt} \qquad i = 1, 2 \ldots 16 \qquad and\, j = 1, 2 \ldots 16$$

where m_{ij} is the import share of country *i* from country *j* relative to its total imports from the other 15 sample foreign countries. Besides, variables y_{jt} and r_{jt} are respectively the GDP and business R&D expenditure of country *j*. Lastly, r^{*}_{it} is the amount of foreign R&D expenditure in country *i* and r_{jt} is the amount of the business R&D expenditure of country *j*.

Following Acharya and Coulombe (2006), the estimation of the model has been carried out using Feasible Generalized Least Square (FGLS), Seemingly Unrelated Regression (SUR) and 2SLS techniques. Each technique has its own benefits. Time-series cross-section (TSCS) data is defined according to Beck and Katz (1995): "Time-series cross-section data are characterized by having repeated observations on fixed units, such as states or nations. The number of units analyzed would typically range from about 10 to 100, with each unit observed over a relatively long time period (often 20 to 50 years). Both the temporal and spatial properties of TSCS data make the use of ordinary least squares (OLS) problematic". (Beck and Katz (1995, p.1))

As stated by Beck and Katz (1995), in order to estimate TSCS data with the best unbiased estimator, the homoscedasticity of all error terms must be considered. Doing so, the OLS will be the best unbiased estimator for the TSCS data. More precisely, if the error terms are not spherical, the OLS estimator will not be optimal. The second method proposed by Beck and Katz (1995) to estimate TSCS data is the GLS method. This method can only be used for estimating

TSCS data as long as the variance-covariance matrix of errors is known. Beck and Katz (1995) argue that the GLS leads to underestimating parameters since it assumes that all the information about the error process is known. Thus, the biggest limitation in estimating models with TSCS data is heteroscedasticity. Beck and Katz (1995) indicates that to overcome this limitation, Parks (1967) proposed the use of the FGLS estimator, in which the errors show panel heteroscedasticity, contemporaneous correlation, and unit specific serial correlation. It is called "feasible" GLS because it uses an estimation of the error process without the assumption of having a known error process. (Beck and Katz (1995, p.5))

Another estimator proposed by Parks (1967) is the Seemingly Unrelated Regression (SUR), which assumes that the errors are both cross-sectional heteroscedastic and contemporaneously correlated. However, Parks estimations are known to potentially produce standard errors which lead to an extreme confidence, particularly when the number of time series is not much larger than the number of cross-sections. (Beck and Katz (1995, p.4))

Following Acharya and Coulombe (2006), Consistent Standard Errors (HCCME) is reported to provide a measure of underestimating true sampling variability of the Parks standard errors. In other words, as stated by Beck and Katz (1995), HCCME shows how much the Parks method falsely inflates confidence in the findings of TSCS studies. Results from the SUR estimation are also presented. As expected, SUR estimations generate higher t-statistic compared to FGLS.

Moreover, in the light of Acharya and Coulombe (2006), the model has been estimated with the instrumental variables (IV) technique in order to overcome a potential endogeneity problem and measurement errors. It is important to mention that all IV estimations include log levels of labour productivity lagged by two years ($Y_{i,t-2}$).[6] The other instrument variables are population growth, investment-to-GDP ratio and openness, all lagged by one year. To end this section, it is worthwhile to note that iterated weighted two- stage least-squares (2SLS) estimations are equivalent to IV system of FGLS estimations.

[6] Following Acharya and Coulombe (2006), this major paper includes two year lagged values of log level of labour productivity in order to reduce the propensity of overestimating the convergence speed which results from measurement errors (Barro and Sala-i-Martin, 2004) and to decrease Stephen Nickell's (1981) bias of fixed effect estimations of dynamic TSCS models.

6. Results

6.1. Estimation results for the period 1981 to 2009 using the standard R&D expenditure intensity

This section presents results for the same standard R&D intensity variables as used in Acharya and Coulombe (2006) but the period is extended to 2009. All regression results are reported in Tables 3 to 8. Table 3 presents the estimation of equation (3) for the effect of the total public R&D expenditure (PERD), which is the sum of the higher education (HERD) and the government R&D (GOVERD) expenditure. The results in Tables 4 and 5 refer to the effects of GOVERD and HERD respectively.

The three tables show that for all the techniques used for estimation (FGLS, SUR and 2SLS), the coefficients for lagged labour productivity, business cycle component, investment intensity, and openness are significant and robust. In addition, their sign is consistent with what we would expect. The coefficient for the lagged productivity level is negative, which demonstrates the existence of conditional convergence. Results for the lagged productivity are significant at least at 1% level. The different estimated values of the lagged productivity coefficients indicate that the convergence speed varies between 4.4% and 6%, which means that the economy moves half way towards a steady state in about 11.7 to 15.9 years.

This range of convergence speed is consistent with the other neo-classical cross-country studies such as Barro and Sala-i-Martin (2004). However, this major paper's estimated convergence speed is slower compared to the findings of Acharya and Coulombe (2006). Based on Acharya and Coulombe's estimations, the convergence speed between OECD countries lies between 6.7% and 11.7%. This range indicates that the half-life of convergence is about 6 to 12 years.

As predicted from the neo-classical framework, the coefficient of the population growth is negative and significant at least at 5% level. This implies that the population growth has a negative impact on labour productivity; this finding is consistent with the prediction of the neo-classical growth model. Also, the coefficient of the investment intensity is positive and significant at least at 5% level, which indicates that as the share of investment rises, productivity growth increases in parallel. This is also in line with the prediction of neo-classical growth model.

The point estimate for business cycle component is positive and significant at least at 10% level for three different measures of public R&D expenditure intensity through the FGLS and SUR techniques and positive but insignificant for total and higher education specification through 2SLS technique.

Comparing Tables 3, 4 and 5 demonstrates that the domestic business R&D expenditure (BERD) has a positive and significant effect on labour productivity growth rate. The positive effect of BERD in this study is robust, because for all the specifications (GOVERD, HERD and PERD) and the techniques (FGLS, SUR and 2SLS), all nine estimation results show that the coefficients of BERD are positive and significant at least at 5% level. It is important to mention that for all the specifications, the adjusted R^2 estimated through the FGLS and the SUR techniques is in the range of 0.11-0.12 and 0.40-0.44 respectively. As observed from the tables, the SUR technique gives a higher R^2 for each estimation. As discussed earlier, in TSCS models, the SUR method underestimate the standard errors, leading to overconfidence. Thus, the R^2 and t-ratios are larger in SUR estimations compared to FGLS and 2SLS.

According to Nadiri (1993), the long-run output elasticity with respect to the business R&D varies between 8% to 30% at the industry level and 10% to 30% at the firm level. This range of elasticities falls if the labour productivity growth is used as a dependent variable. For instance, in Acharya and Coulombe (2006), the long-run elasticity of labour productivity with respect to business R&D expenditure varies between 0.24% and 0.5%. Based on this major paper's regression results, the same elasticity varies between 0.1% and 0.25%. Thus, if the business R&D intensity increases by 10%, the long-run level of the labour productivity will increase between 1% and 2.5%. Following the approach of Acharya and Coulombe (2006), this result indicates that with a given average business R&D expenditure intensity of 1.3 for the sample of OECD countries used in this major paper, a 10% increase in R&D expenditure leads to an increase in R&D that measure about 0.13% of GDP. Therefore, using elasticities calculated previously, if R&D increases by 0.1% of GDP, the labour productivity will increase by 0.8% to 1.9%. Considering an average population growth rate of 0.5% among sample countries, an increase is R&D measuring 0.1% of GDP leads to a 0.4% to 1.0% increase in GDP per capita.

The point estimate of foreign R&D expenditure is positive, but insignificant for the PERD specification using FGLS, SUR and 2SLS method, and negative and insignificant for both the HERD and GOVERD specifications through FGLS and 2SLS and positive but insignificant for HERD through the SUR method. As stated by Acharya and Coulombe (2006), the insignificance of the foreign R&D coefficient is due to the inability of the import channel to completely transfer the spill-over effects of the foreign R&D expenditure onto the domestic labour productivity. Specifically, these results are not related to the foreign R&D spill-over. As mentioned in section 2, to compute the foreign R&D spill-over, it is better to regress the effect of the foreign R&D expenditure on TFP growth rate.

Finally, results for the three alternative public R&D measures (GOVERD, HERD, and PERD) are found to be not as robust. There is no evidence of a positive effect of the public R&D expenditure on the domestic labour productivity growth for any of the three aforementioned measures. Thus, we fail to accept that PERD (Table 3), GOVERD (Table 4) and HERD (Table 5) have a positive effect on the labour productivity growth rate. As reported in Table 3, the coefficient of PERD is negative and even significant at least at 5% level for FGLS and SUR method. Table 4 shows that the coefficient of GOVERD is also negative and insignificant for FGLS and 2SLS and negative and significant for SUR at least at 1% level. As discussed earlier, based on Beck and Katz (1995), SUR estimators underestimate the standard error which leads to overconfidence. Thus, when the results of SUR and FGLS are not the same, results of FGLS are more reliable. Table 5 indicates that the effect of HERD on labour productivity is negative and insignificant for FGLS, SUR and 2SLS methods.

One reason for the insignificance of the public R&D coefficient could be that it mostly concentrates on fundamental research such as military technology or public health which are not business oriented or profit seeking. Consequently, compared to business R&D, it is less sensitive to changes in the market conditions. Thus, the public R&D fluctuates less than the GDP and also has smaller correlation with the GDP growth rate. However, this major paper's results are in contrast to those presented in Acharya and Coulombe (2006), where HERD is reported to have a positive effect on labour at least at 5% level. This is notably because this paper's estimation period includes the financial crisis of 2008. As discussed in section 3.2, there is a time lag of one to two years between the fluctuations of the R&D expenditure and the business cycles. Since due to the lack of data, this major paper only covers one year after the financial crisis, i.e. up till 2009, the results are not so robust.

In order to better demonstrate the effect of the economic recession of 2008 in the regression analysis, the model is estimated two more times, once with the adjusted R&D expenditure using data until 2009 and once for the time period of 1981-2000. This approach will enable comparison between the results of this major paper with those of Acharya and Coulombe (2006). The results are reported in section 6.2 and 6.3 respectively.

Table 3. Effects of total standard public R&D and standard business R&D on labour productivity growth

Dependent variable: change in log labour productivity

Standard R&D expenditure intensity: R&D expenditure as a ratio of actual GDP

Number of observations = 448 (sample period: 1981-2009)

Number of countries = 16

	FGLS	SUR	2SLS
Lagged labour productivity	-0.054	-0.06	-0.047
	(-3.11)[a]	(-3.94)[a]	(-2.71)[a]
Business cycle	0.150	0.057	0.053
	(2.09)[b]	(1.51)[c]	(1.19)
Investment intensity	0.027	0.034	0.014
	(3.19)[b]	(7.31)[a]	(1.50)
Population growth	-0.009	-0.012	-0.008
	(-3.44)[a]	(-7.72)[a]	(-2.90)[a]
Openness	0.015	0.026	0.009
	(1.70)[b]	(7.44)[a]	(1.01)
Germany dummy	0.0003	-0.005	-0.001
	(0.06)	(-0.33)	(-0.25)
Foreign BERD	0.011	0.015	0.010
	(0.33)	(0.79)	(0.26)
Domestic BERD	0.010	0.009	0.011
	(2.39)[b]	(5.58)[a]	(-1.72)[b]
Domestic PERD	-0.015	-0.023	-0.012
	(-2.24)[b]	(-6.95)[a]	(0.17)
Long-term elasticities			
Foreign BERD	-	-	-
Domestic BERD	0.19	0.15	0.23
Domestic PERD	-0.28	-0.38	-
Adjusted R^2	0.12	0.44	
S.E. of regression	0.02	0.02	
Durbin-Watson	1.40	1.78	

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one year. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 percent level

[b] indicates significance at 5 percent level

[c] indicates significance at 10 percent level

Table 4. Effects of standard government R&D and standard business R&D on labour productivity growth

Dependent variable: change in log labour productivity

Standard R&D expenditure intensity: R&D expenditure as a ratio of actual GDP

Number of observations = 448 (sample period: 1981-2009)

Number of countries = 16

	FGLS	SUR	2SLS
Lagged labour productivity	-0.057	-0.059	-0.045
	(-3.23)[a]	(-4.11)[a]	(-2.51)[b]
Business cycle	0.160	0.092	0.059
	(2.22)[b]	(2.64)[a]	(1.32)[c]
Investment intensity	0.025	0.030	0.015
	(2.87)[b]	(6.56)[c]	(1.54)[c]
Population growth	-0.008	-0.009	-0.007
	(-2.99)[b]	(-5.98)[b]	(-2.72)[b]
Openness	0.016	0.030	0.012
	(1.88)[c]	(7.53)[a]	(1.25)[b]
Germany dummy	0.0001	-0.005	-0.001
	(0.02)	(-0.32)	(-0.27)
Foreign BERD	-0.015	-0.014	-0.036
	(-0.46)	(-0.73)	(-1.04)
Domestic BERD	0.008	0.006	0.009
	(1.85)[c]	(-3.60)[a]	(2.03)[b]
Domestic GOVERD	-0.003	-0.005	-0.002
	(-0.72)	(-2.98)[a]	(0.70)
Long-term elasticites			
Foreign BERD	-	-	-
Domestic BERD	0.14	0.10	0.20
Domestic PERD	-	-0.09	-
Adjusted R^2	0.11	0.40	
S.E. of regression	0.02	0.01	
Durbin-Watson	1.40	1.8	

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one year. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 percent level

[b] indicates significance at 5 percent level

[c] indicates significance at 10 percent level

Table 5. Effects of standard higher education R&D and standard business R&D on labour productivity growth

Dependent variable: change in log labour productivity

Standard R&D expenditure intensity: R&D expenditure as a ratio of actual GDP

Number of observations = 448 (sample period: 1981-2009)

Number of countries = 16

	FGLS	SUR	2SLS
Lagged labour productivity	-0.052	-0.049	-0.044
	(-3.01)[a]	(-3.43)[a]	(-2.47)[b]
Business cycle	0.166	0.097	0.047
	(2.38)[b]	(2.73)[a]	(1.05)
Investment intensity	0.029	0.032	0.016
	(3.27)[a]	(7.35)[a]	(1.64)[c]
Population growth	-0.007	-0.009	-0.005
	(-2.81)[a]	(-6.22)[a]	(-2.11)[b]
Openness	0.016	0.030	0.014
	(1.93)[a]	(8.02)[a]	(1.61)[c]
Germany dummy	-0.001	-0.001	-0.002
	(-0.36)	(-0.62)	(-0.52)
Foreign BERD	-0.016	0.020	-0.032
	(-0.49)	(-0.95)	(-0.92)
Domestic BERD	0.010	0.007	0.011
	(2.36)[b]	(4.55)[a]	(2.4)[b]
Domestic HERD	-0.015	-0.007	-0.009
	(-2.64)	(-5.97)	(-1.65)[c]
Long-term elasticities			
Foreign BERD	-	-	-
Domestic BERD	0.19	0.14	0.25
Domestic PERD	-	-	-0.25
Adjusted R^2	0.12	0.42	
S.E. of regression	0.02	1.02	
Durbin-Watson	1.41	1.81	

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one year. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 percent level

[b] indicates significance at 5 percent level

[c] indicates significance at 10 percent level

6.2. Estimation results for Adjusted R&D expenditure over the period 1981 to 2009

We now estimate the model using the adjusted R&D expenditure intensity data with the FGLS method. This major paper uses the adjusted R&D expenditure intensities which are less responsive to the business cycles in order to see whether the effectiveness of R&D expenditure intensity is affected when such variables are used in the regression which are not by construction sensitive to the business cycle. It is worthwhile to note that due to the size of the recession in 2008, this analysis is particularly important over the period of 1981-2009 .The estimation results are reported in Table 6.

Using the adjusted R&D expenditure intensities in the regression, the point estimates for the lagged labour productivity, population growth rate and investment intensity are significant and robust. Also their signs are consistent with the neo-classical framework. An important shift from the previous approach is that the estimated coefficient for the openness variable now becomes negative and significant at least at a 5% level. In addition, the cyclical component (the GDP gap) is now insignificant.

Consequently, the estimation results for the adjusted R&D intensities are not so robust. The adjusted BERD coefficient for the adjusted PERD and GOVERD specifications is positive but insignificant; while for the adjusted HERD specification, it is negative and significant at least at a 10% level. The point estimate of the adjusted foreign R&D expenditure is positive, but insignificant for the adjusted PERD and negative and insignificant for the adjusted HERD and GOVERD.

Furthermore, among all the adjusted specifications of the public R&D, only HERD has a positive effect on the labour productivity growth. The positive effect of the adjusted higher education is significant at least at a 5% level. The point estimate of the adjusted HERD shows that the long-run elasticity of labour productivity level with respect to the adjusted higher education is 0.14% which means that a typical OECD country that invests 10% more than average in higher education R&D, will experience a 1.4% higher level the labour productivity in the long-run. Following the approach of Acharya and Coulombe (2006), this result indicates that with a given average business R&D expenditure intensity of 0.4 for the sample of OECD countries used in this major paper, a 10% increase in R&D expenditure leads to an increase in R&D that measure about 0.04% of GDP. Therefore, using elasticities calculated previously, if R&D increases by 0.1% of GDP, the labour productivity will increase by 3.5%. Considering an average population growth rate of 0.5% among sample countries, an increase is R&D measuring 0.1% of GDP leads to a 1.7% increase in GDP per capita.

Table 6. Effects of adjusted R&D expenditure on labour productivity growth using FGLS

Dependent variable: change in log labour productivity
Adjusted R&D expenditure: R&D expenditure as a ratio of potential GDP.
Number of observations = 448 (sample period: 1981-2009)
Number of countries = 16

	Total public R&D	Government R&D	Higher education R&D
Lagged labour productivity	-0.074	-0.077	-0.093
	(-4.07)[a]	(-4.16)[a]	(-5.06)[a]
Business cycle	-0.035	-0.038	-0.019
	(-0.46)	(0.50)	(0.27)
Investment intensity	0.014	0.014	0.014
	(2.84)[b]	(2.94)[a]	(3.04)[a]
Population growth	-0.004	-0.004	-0.006
	(-2.17)[b]	(-1.93)[c]	(-3.09)[a]
Openness	-0.019	-0.017	-0.019
	(-2.45)[b]	(7.44)[b]	(-2.77)[a]
Germany dummy	-0.005	-0.005	-0.006
	(-0.91)	(-0.86)	(-1.25)
Foreign BERD	-0.012	0.06	-0.051
	(0.83)[c]	(-2.19)	(-1.85)[c]
Domestic BERD	0.003	0.002	-0.007
	(0.84)	(0.44)	(-1.79)[c]
Domestic public R&D	-0.12	-0.004	0.024
	(-1.82)[c]	(0.44)	(4.81)[a]
Long-term elasticities			
Foreign BERD	-0.16	-	-0.55
Domestic BERD	-	-	0.08
Domestic PERD	-0.16	-	0.26
Adjusted R^2	0.07	0.07	0.13
S.E. of regression	0.02	0.02	0.02
Durbin-Watson	1.40	1.39	1.44

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 percent level
[b] indicates significance at 5 percent level
[c] indicates significance at 10 percent level

6.3. Results of estimation for the period 1981-2000 and its comparison with those of Acharya and Coulombe (2006)

In order to replicate Acharya and Coulombe (2006)'s results, the model has been estimated over the period of 1981 to 2000. This is particularly important because the economic recession of 2008 is not included in this sample. Following this approach, it can be clarified whether the robustness of the results from Acharya and Coulombe (2006) is affected by the economic crisis of 2008. Table 7 shows the estimation result for this period using the FGLS technique. Standard R&D expenditure intensity which is measured as a ratio to the actual GDP is used in this section. The Acharya and Coulombe (2006)'s results are reported in Table 8.

As seen in Table 7, the point estimates for the lagged labour productivity, the business cycle component, investment intensity, and openness are significant and robust. In addition, their signs are consistent with what we would expect according to the neo-classical framework.

Considering the point estimates for the R&D expenditure variables, results are robust and consistent. The estimated BERD coefficients for the all three public R&D expenditure specifications are positive and significant at least at a 1% level. The long-run elasticity of labour productivity with respect to business R&D expenditure computed through the FGLS technique varies between 0.38% and 0.42%. This range is in line with Acharya and Coulombe (2006)'s estimations. In the light of Acharya and Coulombe (2006)'s results, the long-run elasticity of labour productivity with respect to the business R&D fluctuates between 0.24% and 0.43%.

Notably, among the various measures of the public R&D expenditure, only the higher education expenditure has a positive and significant effect on labour productivity growth rate. Results show that a typical OECD country with a 10% higher level of investment in the HERD above the OECD average will experience a 1.5 % higher level of labour productivity. This result is significant at least at a 10 % level.

It is important to mention that using the same sample as Acharya and Coulombe (2006), the analysis in this major paper found results to be consistent and very comparable with those of Acharya and Coulombe (2006). Acharya and Coulombe (2006) concludes that among the three measures of R&D expenditure intensity, only business R&D expenditure has a positive growth effect which is strong and robust. Among the three measures used for public R&D, only higher education has a positive growth effect.

In conclusion, a comparison between the estimation results for the periods 1981-2000 and 1981-2009, indicates that the financial crisis of 2008 had a definite impact on the effectiveness of higher education and business R&D expenditures in the regression analysis. Before the economic recession of 2008, the business and higher education R&D expenditures both had robust and significant effects on the labour productivity growth rate of the OECD countries. In contrast, the estimation results for the period of 1981-2009, which includes the economic crisis of 2008, indicates that only business R&D expenditure has a positive effect on labour productivity growth rate in the long run. The higher education R&D expenditure coefficient for this time period ceases to be positive and significant.

Table 7. Effects of various standard R&D expenditure intensity measures on labour productivity growth over 1981-2000 using FGLS

Dependent variable: change in log labour productivity

Standard R&D expenditure intensity: R&D expenditure as a ratio of actual GDP

Number of observations = 304 (sample period: 1981-2000)

Number of countries = 16

	Total Public R&D	Government R&D	Higher education R&D
Lagged labour productivity	-0.085	-0.082	-0.071
	(-3.61)[a]	(-3.22)[a]	(-3.01)[a]
Business cycle	0.196	0.176	0.207
	(2.14)[b]	(1.88)[c]	(1.72)[b]
Investment intensity	0.028	0.086	0.091
	(2.21)[b]	(6.64)[a]	(2.33)[a]
Population growth	-0.009	-0.011	-0.012
	(-1.70)[c]	(-2.04)[a]	(-2.38)[b]
Openness	0.024	0.020	0.032
	(1.79)[c]	(1.39)[c]	(2.32)[a]
Germany dummy	-0.023	-0.021	-0.019
	(-1.31)	(-1.52)	(1.10)
Foreign BERD	0.057	0.025	0.029
	(1.10)	(0.44)	(0.57)
Domestic BERD	0.032	0.031	0.030
	(4.91)[a]	(4.58)[a]	(3.35)[a]
Domestic Public R&D	-0.031	-0.018	0.011
	(1.10)	(-2.22)[b]	(1.82)[c]
Long-term elasticizes			
Foreign BERD	-	-	-
Domestic BERD	0.38	0.38	0.42
Domestic PERD	-	-0.22	0.15
Adjusted R^2	0.30	0.29	0.28
S.E. of regression	0.02	0.02	0.02
Durbin-Watson	1.84	1.84	1.80

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 [a] indicates significance at 1 percent level

[b] indicates significance at 5 percent level

[c] indicates significance at 10 percent level

Table 8. Effects of various R&D expenditure intensity measures on labour productivity growth results of Acharya and Coulombe (2006) using FGLS

Dependent variable: change in log labour productivity

Number of observations = 304 (sample period: 1981-2000)

Number of countries = 16

	Total Public R&D	Government R&D	Higher education R&D
Lagged labour productivity	-0.099	-0.117	-0.083
	(-3.57)[a]	(-3.89)[a]	(-3.31)[a]
Business cycle	0.262	0.260	0.303
	(3.00)[a]	(2.95)[c]	(3.54)[c]
Investment intensity	0.061	0.063	0.064
	(4.62)[a]	(4.63)[a]	(4.84)[a]
Population growth	-0.011	-0.009	-0.011
	(-1.89)[b]	(-1.57)	(-2.11)[b]
Openness	0.030	0.028	0.033
	(2.42)[b]	(2.07)[b]	(2.59)[a]
Germany dummy	0.040	-0.044	-0.035
	(-2.08)[b]	(-2.30)[b]	(-1.78)[c]
Foreign BERD	0.018	0.001	0.022
	(0.60)	(0.03)	(0.75)
Domestic BERD	0.029	0.028	0.036
	(4.00)[a]	(3.75)[a]	(5.08)[a]
Domestic public R&D	0.012	0.006	0.019
	(1.13)	(0.78)	(2.02)[b]
Long-term elasticities			
Foreign BERD	-	-	-
Domestic BERD	0.29	0.24	0.43
Domestic PERD	-	-	0.23
Adjusted R^2	0.32	0.3	0.38
S.E. of regression	0.02	0.02	0.02
Durbin-Watson	-	-	-

Note: All regressions were estimated in the log forms. The regressions are two-way panel which includes both country and time dummies. The values in parentheses are T-ratios. All business, public and foreign R&D expenditure are lagged by one. The first difference of BERD, PERD and foreign R&D is also included in the regressions.

[a] indicates significance at 1 percent level

[b] indicates significance at 5 percent level

[c] indicates significance at 10 percent level

7. Conclusion

Endogenous growth models introduce R&D expenditure as an engine of economic growth. According to the finding of Acharya and Coulombe (2006), the business R&D expenditure has a positive and strongly significant growth effect on long run labour productivity growth rate while among different measures of public R&D expenditure; only higher education has a positive and significant effect on the labour productivity growth rate.

In the light of this major paper's analysis, the positive and significant effect of business R&D expenditure on labour productivity growth is not as robust as suggested by Acharya and Coulombe (2006). This is mostly because of the following two reasons. First, the regression results using the adjusted R&D expenditure intensity (R&D expenditure as a ratio of potential GDP) indicate that the effect of R&D expenditure intensity on labour productivity is not significant. Consequently, the reported positive effect of business R&D by Acharya and Coulombe (2006) might have resulted from the fact that the standard R&D expenditure (R&D expenditure as a ratio of actual GDP) is more sensitive to the business cycle relative to adjusted R&D expenditure. Second, after including the recession of 2008 into the estimation period, using standard R&D expenditure in the regression gives significant results for the effect of the business R&D expenditure on labour productivity.

Estimation results indicate that over the period of 1981-2009, which includes the biggest economic contraction since 1930; only the business R&D expenditure has had a positive and significant effect on the labour productivity growth rate. The estimated long-run elasticity of labour productivity with respect to business R&D among OECD countries during 1981-2009 varies between 0.1 and 0.25, which is almost half of the long-run elasticity estimations by Acharya and Coulombe (2006). Furthermore, this study found the effect of foreign R&D expenditure on the labour productivity to be insignificant. This does not imply that there is no spill-over effect among the OECD countries for the period of 1981-2009. Instead, this might be due to the inability of the trade channel to fully capture the foreign R&D spillover.

In order to enable comparison between this major paper's results and those of Acharya and Coulombe (2006), the model is estimated once again for the period of 1981-2000. Estimation results show that the business R&D expenditure and most importantly higher education has a positive and significant effect on the labour productivity growth rate for the period of 1981-2000. These results are highly comparable with those of Acharya and Coulombe (2006). Notably, results indicate that the long-run elasticity of labour productivity with respect to the higher education over the period of 1981-2000 was 0.15% for the selected sample of OECD countries. As discussed, estimations results of standard R&D variables over the period 1981-2009 demonstrate no evidence of any positive effect of higher education, government expenditure, or a summation of both, on the long run labour productivity growth rate.

Bibliography

Acharya, Ram C. and Coulombe Serge. (2006) "Research and Development Composition and Labour Productivity Growth in 16 OECD Countries. "Industry of Canada. Working Paper, (February).

Acemoglu Daron. (2007) "*Introduction to Modern Economic Growth.*" MIT Press.

Aghion, Philippe, and Howitt, Peter. (1992). "A Model of Growth through Creative Destruction." *Econometrica* 60, pp.323-351, (March).

Arrow, Kenneth J.(1962) "The Economic Implications of Learning by Doing." Rev. Econ. Studies 29. 155-73, (June).

Beck, Nathaniel and Katz, Jonathan N. (1995) "What To Do (and Not To Do) with Time-Series Cross-Section Data." *American Political Science Review,* 89(3), pp. 634-47, (September).

Barro, Robert J. and Sala-i-Martin, Xavier. (1995) *Economic Growth.* New York: McGraw-Hill.

______. (2004) *Economic Growth.* New York: McGraw-Hill.

Coe, David T. and Helpman, Elhanan. (1995) "International R&D Spillovers." *European Economic Review*, 39(5), pp. 859-87, (May).

Coulombe, Serge. Lee, Frank. C. (1995) "Convergence Across Canadian Provinces, 1961 to 1991", *Canadian Journal of Economics*, 28, 886-898.

Frantzen , Drik. (2000) "R&D, Human Capital and International Technology Spillovers: A Cross-country Analysis." *Scandinavian Journal of Economics*, 102(1), pp. 57-75, (March).

Griffith, Rachel; Redding, Stephen and Reenen, John Van. (2004) "Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries." *Review of Economics and Statistics*, LXXXVI (4), pp. 883-895, (November).

Griliches, Zvi. (1992) "The Search for R&D Spillovers." *Scandinavian Journal of Economics*, 94, pp. S29-47.

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

Griliches, Zvi, and Frank Lichtenberg. (1984) "*R&D and Productivity Growth at the Industry Level: Is There Still a Relationship?*" Chicago: University of Chicago Press for NBER.

Grossman, Gene.M., Helpman, Elhanan.(1991). "Innovation and Growth in the Global Economy". *MIT Press, Cambridge MA.*

Guellec, Dominique and van Pottelsberghe de la Potterie, Bruno. (2003) "The Impact of Public R&D Expenditure on Business R&D." *Economics of Innovation and New Technology*, 12(3), pp. 225-43, (June).

______. **(2001)** "R&D and Productivity Growth: Panel Data Analysis of 16 OECD Countries" *Oxford Bulletin of Economics and Statistics*, OECD Economic Studies, pp. 103-25.

Heston, Alan; Summers, Robert and Aten, Bettina. Penn World Table Version 6.1 [online].Center for International Comparisons, University of Pennsylvania (CICUP). Available at: http://pwt.econ.upenn.edu/php_site/pwt61_form.php

Islam, Nazrul. (1995) "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics,* 110(4), pp. 1127-71, (November).

Keller, Katarina and Poutvaara, Panu. (2003) "Do the Augmented Solow Models Rule? A Contribution to the Empirics of Human Capital, R&D, and Economic Growth." Centre for Economic and Business Research, Discussion Paper: DP 2003-13.

Keller, Wolfgang. (2004) "International Technology Diffusion." *Journal of Economic Literature*, 42(3), pp. 752-82, (September).

______. **(2002)** "Geographic Localization of International Technology Diffusion." *American Economic Review*, 92(1), pp. 120-42, (March).

Mankiw, N. Gregory; Romer, David and Weil, David N. (1992) "A Contribution to the Empirics of Economic Growth." *Quarterly Journal of Economics* , 107(2), pp. 407-37, (May).

Martin,Carmela: Mulas-Granados, Carlos and Sanz Ismael. (2004) "Spatial Distribution of R&D Expenditure and Patent Applications across EU Regions and its Impact on Economic Cohesion." European Economy Group, Working Paper: NO 32/2004.

Nadiri, M. Ishaq. (1993) "Innovations and Technological Spillovers." NBER Working Paper No. 4423, (August).

Nickell, Stephen. (1981) "Biases in Dynamic Models with Fixed Effects." *Econometrica*, 49(6), pp. 1417-26, (November).

Nonneman, Walter and Vanhoudt, Patrick. (1996) "A Further Augmentation of the Solow Model and the Empirics of Economic Growth for OECD Countries." *Quarterly Economic Journal of Economics*, 111(3), pp. 943-53, (August).

Organization for Economic Co-operation and Development. (2003) "The Sources of Economic Growth in OECD Countries", Paris.

______. **(2002)** *Frascati Manual*: Paris

______. **(2005)** Innovation Policies: Innovation in the Business Sector, Paris.

Romer, David. (2012) "*Advanced Macroeconomics*." New York: McGraw-Hill.

Romer, Paul M. (1990) "Endogenous Technological Change." *Journal of Political Economy*, 98(5), pp. S71-S102, (October).

Sala-i-Martin, Xavier; Doppelhofer, Gernot and Miller, Ronald I. (2004) "Determinants of Long-Term Growth: A Bayesian Averaging of Classical Estimates (BACE) Approach." *American Economic Review*, 94(4), pp. 813-35, (September).

Scherer, F. M. (1982) "Inter-industry Technology Flows and Productivity Growth," *Review of Economics and Statistics* 64, pp. 627-634, (November).

St-Amant, Pierre and Van Norden, Simon. **(1997)** "Measurement of the Output Gap: A Discussion of Recent Research at the Bank of Canada." Bank of Canada. Technical report: No 79, (August).

Ulku, Hulya. (2004) "R&D, Innovation, and Economic Growth: An Empirical Analysis." IMF working paper, (September).

Zachariadis, Marios.(2003) "R&D, Innovation, and Technological Progress: A test of the Schumpeterian Framework without Scale Effects," *Canadian Journal of Economics*, Vol 36, No. 3, pp. 566-686, (August).