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A PANEL CAUSALITY ANALYSIS OF THE RELATIONSHIP AMONG RESEARCH AND DEVELOPMENT, INNOVATION, AND ECONOMIC GROWTH IN HIGH-INCOME OECD COUNTRIES

Bulent Guloglu[*] and R. Baris Tekin[**]

Abstract: This study examines possible causal relations among research and development (R&D) expenditures, innovation and economic growth in high income OECD countries. We test for both pairwise and multivariate causal relations by estimating a trivariate panel vector autoregressive (VAR) model through the GMM and panel fixed effects methods. Our bivariate panel causality test results suggest that R&D expenditures Granger cause innovation measured as the number of triadic patents; while technological innovations Granger cause economic growth, as presumed by endogenous growth theory. A reverse causality relation does also exist between economic growth and innovation, that is, the rate of growth of output accelerates the rate of technological change. Our multivariate causality tests further reveal that the market size and the rate of innovation together Granger cause R&D activity; while an increase in national output and R&D intensity jointly Granger–cause technological change. These findings suggest that both the "technology-push" and "demand-pull" models of innovation equally make sense.

Keywords: Economic Growth, Technological Change, Research and Development, Patents, Panel Granger-Causality
JEL Classification: O30, O31, O33, O39

1. Introduction

A fundamental proposition of economic theory is that sustained economic growth is achieved whenever a non-declining marginal product of capital is reached. In earlier neo-classical economic growth models such as Ramsey's (1928), Solow's (1956) or Swan's (1956), the long-run rate of growth of aggregate capital depends on exogenous technological change and population growth rate. In these models, technological progress is attributed a crucial role in sustaining a positive rate of growth in output per capita in the long run, primarily because technological change is assumed to continually offset the problem of diminishing returns to capital. These earlier growth models, however, are heavily criticized for failing to explain one of the key determinants of economic growth, technological progress, since they take the rate of technological change, along with the rate of population growth, as exogenous.

Starting with the pioneering works of Romer (1986) and Lucas (1988), the new growth theory paid a considerable amount of effort to 'endogenize' technological change in the production function (see Aghion and Howitt, 1998). In this more recent corpus of work, often referred to as the "endogenous growth theory", endogenously determined technological change generates sustainable economic growth, assuming constant returns

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to innovative research, in terms of human capital employed in Research and Development (R&D). Endogenous growth models provide a suitable framework to study important issues regarding the role of technological change in the process of economic growth, as well as the design, and efficiency of R&D and innovation policies.

This research aims to analyze empirically the causal relations among R&D expenditures, innovation, and economic growth in 13 high income OECD economies, by making use of annual data for the period between 1991 and 2007. For testing causal relationships among the variables we estimate a trivariate panel vector autoregressive (VAR) model, employing panel fixed effects and Generalized Method of Moments (GMM) methods. This methodology allows us to test for both bivariate (pair-wise) and multivariate Granger causal relations among the variables at hand. Although there exists a well-developed literature on the effectiveness of R&D intensity and the impact of technological change on economic growth, causal relations among these variables remain somewhat under-researched. To the best of our knowledge, no previous work attempted to study the causal relations among R&D effort, innovation, and economic growth in a systematic way. This study aims to fill this gap in the literature by focusing exclusively on the causal directions among R&D intensity, the rate of patenting, and economic growth in the case of high income OECD countries. Different from previous works that studied the relation between R&D and innovation, and innovation and economic growth, this study explicitly tests for the direction of causality among these three variables.

This study finds strong evidence that relations between R&D intensity, technological change, and the rate of growth of output are all positive, as implied by the Schumpeterian framework. Our pair-wise Granger causality test results suggest that R&D intensity triggers innovation measured as triadic patents, while this latter enables economic growth, as presumed by endogenous growth theory. Our multivariate causality test results further suggest a multiplicity of causal directions among R&D, innovation, and economic growth, allowing us to understand the nature and dynamics of the innovation process better. At this level of the analysis, this study provides evidence that R&D activity and technological change together Granger cause economic growth. Similarly, we also show that economic growth and investments in R&D together Granger cause technological change (innovation). Considering the source of inventive activity, our findings about the direction of causality among the variables at hand provide empirical support for both the “demand-pull” and “technology-push” models of innovation. Our test results suggest that both the “demand-pull” and “technology-push” hypotheses are equally relevant for explaining the initial source of technological change in high income OECD economies.

This paper is structured around five sections. The second section provides a concise survey of the related empirical literature. The third section presents the way the variables are defined and specifies the sources of data, before introducing the panel Granger causality testing methodology employed in the study. Next, in the fourth section, we present the findings of our Granger causality test results. The final section concludes the paper.

2. R&D, Innovation, and Economic Growth: A Short Survey of the Literature

This paper adds to the vast empirical literature on the new growth theory. A major research avenue in endogenous growth literature involves testing for the effectiveness of R&D in enabling sustainable economic growth. Most of this literature on the outcome of R&D intensity focuses exclusively on the impact of R&D expenditures on total factor productivity growth[1]. This branch of the literature finds evidence for a positive relation between R&D spending and growth of total factor productivity.[2] Within this line of research, several studies have exclusively focused on the determinants and efficiency of R&D investment at the firm level, providing evidence of a positive relationship between R&D expenditures and productivity growth.[3] At the firm level, the empirical literature suggests that decisions on R&D investment are made similarly to physical capital investment decisions; while the criteria for decision is the rate of return on investment in both of the cases (Wang, 2010).

Empirical literature on R&D investment and productivity growth further comprises numerous studies that employ macro-level aggregate data. In an early empirical examination, Lichtenberg (1992) suggested a positive relationship between R&D expenditures and productivity growth, by introducing the stock of technological knowledge into the neoclassical growth model as an explanatory variable of international differences in productivity growth. Coe and Helpman (1995) found a positive long-term relationship between R&D expenditures and total factor productivity. By making use of aggregate level patent data, Porter and Stern (2000) made it clear that innovation is positively related to human capital in the R&D sectors and national knowledge stock, having a significant impact on total factor productivity growth. Using two-digit industry level data from U.S. manufacturing during the period 1963-1988, Zachariadis (2003) provided strong evidence that in the U.S. economy R&D investment and productivity growth are positively related. More specifically, Zachariadis (2003) found that R&D intensity has a positive impact on the rate of patenting, the rate of patenting has a positive effect on technological progress, and, finally, technological progress has a one-to-one relationship with the growth rate of output per worker. Zachariadis (2003) also found that the intensity of aggregate manufacturing R&D has a stronger impact on the rate of

[1] A non-exclusive list should include Aghion and Howitt (1998), Griliches and Lichtenberg (1984), Jones (1995), and Zachariadis (2003). For a review of the related literature see Wang (2010).

[2] See Aghion and Howitt (1998), Falk (2007), Fraumeni and Okubo (2002), Griffith *et al.* (2004), Griliches and Lichtenberg (1984), and Scherer (1982), among others.

[3] See, for example, Griliches (1986), Griliches and Mairesse (1984) and Wakelin (2001).

patenting than own-industry R&D, implying technological spillovers across industries.

All in all, the empirical literature has repeatedly confirmed that R&D investment has a positive and significant impact on total factor productivity[4]. Regarding the effect of R&D on economic growth, several empirical studies have shown that R&D investments have a positive impact on economic growth rates. In such a study, Fraumeni and Okubo (2002) found that the contribution of returns to R&D capital account for about 10 percent of the growth in real GDP for the US, for the period between 1961 and 2000. Focusing on OECD countries over the period between 1970 and 2004, Falk (2007) confirmed that both the share of total business R&D expenditures in GDP and the share of R&D investments in the high-tech sector have a significant and positive impact on the rate of growth of output per capita. Ulku (2004) provided evidence that innovation has a significant and positive impact on per capita outputs of both developed and developing countries[5]. The author, however, reported that only the larger OECD countries are able to increase their innovation through investment in the R&D sector, while the remaining, lower income OECD countries promote their domestic technological progress by using the know-how generated in other OECD countries.[6]

2.1. On the Sources and Determinants of Innovative Activity

Following the acknowledgement of the role of technological progress in raising total factor productivity and output growth, the question whether technological change is influenced by changes in market demand or by advances in basic scientific knowledge has become a hot button issue in growth economics (Nemet, 2009). Actually, this is quite an old question in economic theory that goes back at least to the early theoretical thinking on the role of technological change in economic development (see Schumpeter, 1975; Usher, 1954, Schmookler, 1966). Mainly, there are two competing alternative views in the literature regarding the source of inventive and innovative activity. The first and older view on what governs inventive activity in the first instance is associated with the Schumpeterian idea that the essential forces behind progress in the economy are innovative technologies. In this view, often referred to as the “science” or

[4] Empirical literature also reveals that, in addition to domestic R&D expenditures, R&D spillovers from industrialized countries have positive effects on the total factor productivity growth in developing countries. On this issue, see Coe and Helpman (1995), Coe *et al.* (1995), Eaton and Kortum (1999), Griffith *et al.* (2004), Guellec and van Pottelsberghe de la Potterie (2001, 2004), Hasan and Tucci (2010), and LeBel (2008). For inter-industry spillovers of R&D, see van Pottelsberghe de la Potterie (1997).

[5] Several studies such as Ginarte and Park (1997) and Teitel (1994) have further shown that expected future income is a major determinant of current per capita R&D expenditures, indicating that while R&D activity promotes GDP growth, GDP growth could also trigger investment in the R&D sectors. On this issue see Braconier (2000).

[6] For an examination of the impact of technology transfer on enterprise performance in lower income developing countries, see Bilgin *et al.* (2012).

"technology-push" approach to innovation, technological innovations introduced through new products or processes are the primary source of economic development. At the core of the "science" or "technology-push" argument lay the idea that progress in basic sciences determines the rate and direction of innovation. In this line of thinking, the supply of technology is the leading force behind innovative activity. There is thus a transmission of knowledge from basic sciences to applied research that results in the design, development, and commercialization of new products (Nemet, 2009). Product innovations play a primary role in the creation of new markets; the supply of new technologies is more important than adaptation to existing patterns of market demand. The market, in this view, emerges as nothing more than a passive recipient of technological innovations.[7] The technology-push approach to innovation suggests a positive relationship between R&D activity and innovation, the causality being from R&D intensity to technological change.

The second view, often referred to as the 'demand-led" or "market-pull" approach to innovation, on the other hand, goes back to the influential study by Schmookler (1966). This view suggests that innovation is primarily a demand-driven phenomenon and that there is a positive relationship between the size of a market and inventive activity (Trott, 2005). This line of thinking is principally based on the contention that profitability of inventions increases with the market size; i.e. the larger the size of an actual or prospective market, the higher will be inventive activity (Nemet, 2009; Wang, 2010). Unlike the science, or technology-push model, this approach places the emphasis on market demand conditions. In this view, it is the demand, or 'needs' of customers that matter most in the emergence of new products. Schmookler's (1966) approach suggests a pro-cyclical behavior of R&D activity and innovation, foreseeing a unidirectional causality from demand to inventive activity and technological change. Innovation follows the market demand; the rise in economic output, therefore, is coupled with a rise in R&D activity and innovation in the long run[8].

Empirical evidence supporting the demand-pull hypothesis is also plentiful. [9] Schmookler (1966), himself, provided empirical evidence supporting his demand-pull hypothesis by making use of US data. He showed that the level of patent applications is strongly correlated with the level of output or, in the case of capital goods industries, with investment in physical capital. Wyatt (1986) tested Schmookler's hypothesis, and

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[7] See Trott (2005). For a review of the Demand-pull/Technology-push debate in theoretical and applied economic growth literature also see Coombs *et al.* (1987).

[8] Several empirical studies suggested that the positive relationship between the market size and innovative activity exist even in the short-run as short run temporary fluctuations in demand might considerably affect firms' research and development decisions (see Frantzen, 2003). This is primarily because although firms take R&D decisions within a long-term prospect, inventive activity might still be affected by short term temporary fluctuations in demand, since finance for risky and high return investments is more likely to be available in periods of booming demand (Stiglitz 1993).

[9] For a survey of the empirical literature, see Frantzen (2003).

confirmed that physical capital investments Granger cause patent applications in capital goods industries. Lach and Schankerman (1989) also provided evidence supporting the demand pull hypothesis in their Granger causality analysis. Kleinknecht and Verspagen (1990), however, reported much lower coefficients between demand and innovation, re-estimating Schmookler's original regressions. As to the direction of causality between the two variables, the authors found no support for the unidirectional interpretation of Schmookler (1966), but instead, claimed that there is a bidirectional relationship between demand and innovation.

Several empirical studies on the sources of innovative activity, suggested that both the 'demand-pull' and 'technology-push' hypotheses might hold true (see Stoneman, 1979; Scherer, 1982; Bosworth and Westaway, 1984; Kleinknecht and Verspagen, 1990). Unlike the earlier demand-pull and technology-push models, the "interactive model" developed in the 1980s and 1990s places the emphasis on combinations of push and pull effects in explaining the driving force behind innovation in the economy (Trott 2005). In the neo- Schumpeterian view, the demand-pull and technology- push effects on inventive activity are seen as complementary (Frantzen, 2003). In this view, what determines the relative importance of the two alternative effects is the type of industries and innovation (Freeman *et al.* 1982; Freeman, 1994; Walsh, 1984).

3. Data and Methodology

3.1. Definitions of the Variables and Data Sources

In this study we employ data on 13 OECD countries over the period 1991-2007. The countries under study are Australia, Canada, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Portugal, Spain, United Kingdom and the United States. Our exclusive focus on high income OECD countries stems from the fact that the bulk of R&D investment and patent applications throughout the world are concentrated in these countries. We exclusively focus on high income countries also because the literature has made it clear that there is no significant relationship between R&D expenditures and economic growth in low income countries.[10]

"Research and Development" is defined in the widely cited Frascati Manual of the OECD as comprising "creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications" (OECD, 1993, p.29). Following the Frascati Manual, the convention in the literature is to measure R&D by the Gross Domestic Expenditures on R&D (GERD) that is calculated as the ratio of R&D expenditures to GDP (Falk, 2006). GERD provides an

[10] It has been widely noted that there is no link between R&D investment and economic growth in lower income countries, despite the fact that the poorer countries invest more of their national income in R&D than middle income countries do. See Birdsall and Rhee (1993) and Gittleman and Wolff (2001).

internationally comparable measure that accounts for innovative activity in a given country, regardless of differences in the source of financing or sectors (Falk, 2006).

When measuring innovation, we use the number of patents (PATENT) issued during a year. Patents counts provide a good measure of intermediate output of innovative activity[11]. Instead of using patents issued by a given patent office as is the convention in the literature, however, we choose to employ triadic patent families developed by the OECD. Triadic patents are based on patent indicators taken at the three largest patent offices, namely the European (EPO), Japanese (JPO), and American (USPTO) patent offices. Triadic patent families provide a better measure than traditional single office patent indicators since most significant or valuable innovations throughout the world are patented simultaneously in all the three major patent agencies. Triadic patents are a better measure of innovative activity also because they are devoid of the 'home bias', and they provide a higher level of international comparability (de Rassenfosse and van Pottelsberghe de la Potterie, 2009).

The size of the economy is measured by Gross Domestic Product (GDP). Both Gross Domestic Expenditure on R&D and Gross Domestic Product are expressed in million PPP$. We normalize the number of patents, GDP and R&D by population. All data were obtained from OECD database which is available on http://stats.oecd.org/.

3.2. Panel Granger-Causality Testing Methodology

As the short survey of the empirical endogenous growth literature presented above has made it clear, at the heart of the debates on the sources of inventive activity lay the nature and directions of multiple relations among R&D activity, technological change, and economic growth. The present paper employs panel Granger-causality tests to study these multiple relations. Explicit causality analyses of relations among R&D, innovation, and economic growth are rare. To our knowledge, no systematic causality analysis has been performed so far on the possible causal relationships among these three variables[12].

In this paper, we employ panel Granger-causality tests and estimate test equations using panel fixed effects and the GMM methods. This methodology provides a most suitable tool to examine competing hypotheses regarding the source, determinants and consequences of inventive activity. The Granger causality test is a useful device to determine whether the lags of a variable, say, z_{it} contribute to a better forecasting of y_{it}

[11] Several empirical studies made use of patents to measure innovation resulting from investment in the R&D sector. See, for example, Acs *et al*. (2002), Lanjouw and Schankerman (2004), and Pakes and Griliches (1980), among others. For the R&D and Patents relationship, see de Rassenfosse and van Pottelsberghe de la Potterie (2009).

[12] With a small number of exceptions, such as Frantzen (2003), which examines causality relations between R&D activity and total factor productivity growth in the manufacturing sectors of 14 OECD countries.

when the lagged values of z_{it} are introduced into the regression of y_{it} on the lagged values of y_{it} and z_{it}. In the panel data context the Granger non-causality can be tested using a panel VAR model, which can be written in compact form as follows:

$$\begin{bmatrix} y_{1,it} \\ y_{2,it} \\ y_{3,it} \end{bmatrix} = \begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix} + \begin{bmatrix} \Gamma_{11} & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{21} & \Gamma_{22} & \Gamma_{23} \\ \Gamma_{31} & \Gamma_{32} & \Gamma_{33} \end{bmatrix} \begin{bmatrix} z_{1,it} \\ z_{2,it} \\ z_{2,it} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1,it} \\ \varepsilon_{2,it} \\ \varepsilon_{3,it} \end{bmatrix} \quad i=1,2\ldots N \quad t=1,2,\ldots T. \qquad (1)$$

where z_{1it}, $z_{2it,}$ and z_{3it} represent the lagged values of y_{1it}, $y_{2it,}$ and y_{3it} respectively, the terms α_i stand for individual effects which can be eliminated by taking the first difference of equation 1.

The hypothesis that y_2 does not Granger cause y_1 can be tested by imposing the following restriction on the parameters of equation 1.

$$H_0{:}\Gamma_{12}=0$$

If we use the Wald test, only the unrestricted model has to be estimated. It should be noted that the correlation between lagged values of dependent variable and the disturbance terms should be taken into account when estimating equation 1. In the presence of correlated disturbances with the lagged values of dependent variable, estimation of equation 1 by the fixed effects method is inconsistent when T and N are small and it is consistent when T and N tend to infinity. However the Generalized Method of Moments (GMM) estimator may produce consistent and asymptotically efficient estimates, especially when T is small. Since the number of periods is close to the number of countries under study, in this paper we use both methods. One final point which needs to be made is that Granger causality test assumes stationarity of the variables under consideration. Therefore, before testing causality, the stationarity properties of variables should be analyzed.

4. Findings

4.1. Preliminary Data Analysis: Unit Root Tests

To analyze the time series properties of the variables, we carry out the Maddala-Wu (1999), Levin *et al*. (2002), Im-Pesaran-Shin (2003), Hadri (2000) and Pesaran's CADFbar (2007) tests. The reasons for the use of several alternative tests are: 1) Tests differ in their specification of null and alternative hypotheses 2) Except for the CADFbar (2007) test the other tests do not allow for contemporaneous correlations. To test the significance of cross-sectional correlations we use the Pesaran CDLM test (2004). We expect that the use of several tests can improve the robustness of the results. The CDLM test and panel unit root test results are illustrated in Table 1, Table 2 and Table 3.

The results in Table 1 show that the contemporaneous correlations are highly significant across cross-sections.

Table 1. Cross-Section dependence test results

	Intercept	Intercept+trend
PATENT	99.65***	119.22***
GDP	99.06***	116.84***
R&D	107.62***	134.34***

All variables are in logarithmic form. Statistics are significant at *** 1% level of significance, ** 5% level of significance, * 10% level of significance

This result indicates that there is a problem of cross-sectional dependence. As pointed out above, the Maddala-Wu (1999), Levin *et al.* (2002), Im-Pesaran-Shin (2003), Hadri (2000) tests do not allow for cross-sectional dependence. Therefore, in order to reduce the problem, we take average across the series at each point in time and then subtract it from each cross-sectional observation at point t. We then apply panel unit root tests to the resulting series. The panel unit root test results are illustrated in Table 2 and Table 3. As can be seen from the tables, the Maddala-Wu (1999), Levin *et al.* (2002), Im-Pesaran-Shin (2003) test statistics are not significant at the 5 percent level of significance. Therefore, we accept the null hypothesis of a unit root for all series. The Hadri test statistic which is highly significant shows that the null hypothesis of stationarity can be rejected for all series at the 1 percent level of significance. Except for the PATENT series (with intercept and trend) the CADFbar test also accepts the null hypothesis of unit root for the remaining series. Therefore, in the remaining analyses we take the first difference of all the series.

Table 2. Panel unit root tests results (intercept, no trend)

	Levin. Lin and Chu	Im. Pesaran Shin	Maddala – Wu	Hadri	$CADF_{bar}$
PATENT	-1.37*	2.05	30.41	7.29***	-1.989
GDP	-2.39*	0.44	4.24	9.11***	-1.255
R&D	0.62	3.38	2.89	9.10***	-1.105

All variables are in logarithmic form. Statistics are significant at *** 1 % level of significance, ** 5 % level of significance, * 10 % level of significance

Table 3. Panel unit root tests results (intercept and trend)

	Levin. Lin and Chu	Im. Pesaran Shin	Maddala – Wu	Hadri	$CADF_{bar}$
PATENT	-1.14	0.35	22.55	6.49***	-3.076***
GDP	-0.74	0.21	24.48	4.32***	-1.425
R&D	-0.84	-0.78	22.08	4.75***	-1.137

All variables are in logarithmic form. Statistics are significant at *** 1 % level of significance, ** 5% level of significance, * 10% level of significance

4.2. Panel Granger Causality Test Results

To test Granger causality among variables, we use a trivariate panel VAR model. As explained above, the correlation between the lagged values of dependent variables and disturbances terms leads to inconsistent estimates if equation 1 is estimated via pooled OLS. However there are other estimators such as the GMM, Instrumental Variables etc. which produce consistent estimators. Compared to the instrumental variables estimator, the GMM estimator which uses more instruments (especially dynamic instruments) can produce more efficient estimates. In this study, we employ the GMM procedure suggested by Arellano-Bond (1991). It should be noted that fixed effect method can outperform the GMM when T is larger than N. Since T=17 and N=13 in our study, we also use this method. Table 4 reports the results of the Wald test of no causality in the Granger sense, when equation 1 is estimated through the GMM and fixed effects methods. The numbers of causality relations found among the variables are very close to each other; that is, we find eight causal relationships with the GMM and six causal relationships with fixed effect methods. Notice that the Arellano-Bond (1991) test of no serial correlation and the Sargan test of overidentifying restrictions results are illustrated in Table 5. The AR (1) and AR (2) test statistics indicate that there is no serial correlation of order higher than 1. Thus, there is no model misspecification and the moment conditions are valid. Furthermore the Sargan test of overidentifying restrictions shows strong evidence for the null hypothesis that overidentifying restrictions are valid.

Table 4. Causality test results

DIRECTION OF CAUSALITY	GMM (WALD TEST)	NUMBER OF LAGS	Fixed Effects Method (WALD TEST)
RD → PATENT	10.06**	5	20.97***
GDP → PATENT	17.69***	5	20,45***
RD,GDP →PATENT	98.92***	5	38.05***
PATENT →GDP	28.22***	2	4.67
RD → GDP	50.20***	2	0.53
PATENT,RD →GDP	258.51***	2	6.24
PATENT → RD	4.63	5	21.65***
GDP → RD	19.68***	5	15.85***
PATENT,GDP→RD	162.77***	5	37.40*

Lag lengths are chosen so that there is no serial correlation in the first differenced disturbances. All variables are in logarithmic form and first differenced. Statistics are significant at: *** 1 % level of significance, ** 5 % level of significance, * 10 % level of significance

Focusing on the Wald test results obtained through the GMM method we find clear evidence that both R&D intensity and the rate of innovation have a positive impact on, and Granger cause economic growth, as suggested by the new growth theory. The Wald test statistics are highly statistically significant for both methods of estimation. At the multivariate level this finding also holds true; R&D expenditures and innovations together Granger cause economic growth. No matter what the method of estimation is, the Wald test statistics are significant at the 1 percent level of significance. There is therefore a significant positive causal relationship between R&D intensity and innovation, and between innovation and economic growth. These results suggest that endogenous technological change, generated through investment in the R&D sector, is able to promote economic growth. We therefore conclude that R&D based endogenous growth models are relevant in explaining economic growth in high income OECD countries.

Table 5. Autocorrelation and Sargan test of overidentifying restrictions

Model	AR(1)	AR(2)	Sargan Test
PATENT	-2.351(0.0187)	-0.01158(0.9908)	109.7237(0.2829)
GDP	-2.431 (0.0151)	0.48102 (0.6305)	114.18(0.068)
R&D	-1.7921(0.0731)	-1.2375 (0.2159)	11.798(0.8122)

PATENT, GDP and R&D represent PATENT, GDP and R&D equations respectively. Numbers in parentheses are the p-values.

Our Granger causality test results further suggest that R&D expenditures increase with the market size and the rate of innovation in high income OECD economies. This latter causality direction reflects that as long as it pays -- in terms of new processes and products -- firms continue to raise their R&D investments. A possible explanation for the former direction of causality from GDP to R&D expenditures, on the other hand, could be that firms spare more and more funds to R&D activity during periods of sound economic growth. We also find evidence at the multivariate level that innovation and market size together Granger cause R&D investments. This finding suggests that as long as the economy keeps growing and the rate of innovation is rising, firms accelerate R&D intensity.

Regarding the initial source of innovations we have also identified a clear cut result in this study. Our test results suggest that both R&D expenditures and the level of GDP Granger cause technological change, or innovation. This finding is robust to the choice of estimation method; for both the GMM and fixed effects methods, we observe that the test statistics are significant at the 1 percent level of significance. Our multivariate causality test also shows that R&D intensity and GDP growth together Granger cause the rate of patenting, implying that technological change in the economy depends on the size of the market and investment in technological knowledge together. This finding supports the technology-push model of innovation that suggests that a new invention is pushed through R&D intensity on the market. The latter finding that the level of GDP Granger causes innovation is supportive of the idea that innovations are pro-cyclical; an idea that goes back to Schmookler (1966). However, it should be noted that unlike Schmookler (1966) and Wyatt (1986) which foresees a unidirectional causality relation that goes from the market to innovation, this study provided evidence for a mutual dependence of the market and innovation. Therefore, this paper supports the Neo-Schumpeterian view that both the scientific knowledge and market size affect the level of innovations. The interactive model of innovation which places the emphasis on combinations of "push" and "pull" effects in explaining technological change seems to be a more accurate model of understanding the nature of technological progress.

5. Conclusion

This study has shown that relations between R&D and innovation, R&D and economic growth, and economic growth and innovation are all positive and significant. The panel Granger-causality test results provide important insights regarding the causal relationships among R&D, innovations and economic growth in high income OECD economies. First, this study has shown that R&D investments Granger cause technological change, and technological change Granger cause economic growth in high income OECD countries. Our panel Granger-causality tests yield unambiguous evidence regarding the role of R&D activity in generating technological change. Our bivariate test results further suggest that the causality between R&D and technological change might also work in the reverse direction; i.e. from innovations to research and development intensity. This finding suggests that successful investment in the R&D sector eventually trigger further investment in research and experimental development activities. At the multivariate level, we also confirmed that R&D activity together with the rate of patenting Granger cause economic growth.

The empirical evidence presented in this study is in accordance with the expectations of the theoretical literature on the impact and efficiency of R&D activity and the role of technological change in accelerating the rate of growth of national output. The causality directions found in this study obviously support the Schumpeterian view that investments in R&D sectors generate innovation and enhance the rate of growth of the economy. There is therefore room for policies to enhance R&D activity for accelerating technological progress and economic growth in the group of countries examined. Our multivariate causality tests reveal that there exists a multiplicity of causal relationships among the variables at hand. Broadly, we have identified that the market size (GDP) and the rate of innovation (the rate of patenting) together Granger cause R&D activity in the market. This finding supports the idea that R&D investment increases with the size of the market, and successful inventive activity translates into higher investment in the R&D sector. Again, we also find that increases in national income and R&D expenditures jointly Granger–cause innovation. This finding suggests that both inventive activity and innovation are pro-cyclical, as suggested by Schmookler (1966). This reverse causality direction between economic growth and technological change indicates that the demand-pull model of innovation also makes sense in the context of high income OECD countries. In the context of this group of economies, therefore, this study suggests that both the "technology-push" and "demand-pull" effects are equally present, and both models are equally relevant for explaining the source of technological change.

References

Acs, Z.J., Anselin, L., and Varga, A., 2002. Patents and innovation counts as measures of regional production of new knowledge. *Research Policy*, 31(7), pp.1069-1085.

Aghion, P. and Howitt, P., 1998. *Endogenous growth theory*. Cambridge, Massachusetts: MIT Press.

Arellano, M. and Bond, S., 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Review of Economic Studies*, 58(2), pp.277-297.

Bilgin, M.H., Lau, C.K., and Karabulut, G., 2012. Technology transfer and enterprise performance: A firm-level analysis in China. *Journal of Business Economics and Management* (forthcoming).

Birdsall, N. and Rhee, C., 1993. Does R&D contribute to economic growth in developing countries? World Bank, Policy Research Department - *Policy Research Working Paper,* 1221.

Bosworth, D. and Westaway, T., 1984. The influence of demand and supply side pressures on the quantity and quality of inventive activity. *Applied Economics*, 16(1), pp.131-146.

Braconier, H., 2000. Do higher per capita incomes lead to more R&D expenditure? *Review of Development Economics*, 4(3), pp.244-257.

Coe, D.T., Helpman, E., and Hoffmaister, A.W., 1995. North-South R&D spillovers. *NBER Working Paper*, 5048.

Coe, D.T. and Helpman, E., 1995. International R&D spillovers. *European Economic Review*, 39(5), pp.859-887.

Coombs, R., Saviotti, P., and Walsh, V., 1987. *Economics and technological change.* New Jersey: Rowman and Littlefield.

de Rassenfosse, G. and van Pottelsberghe de la Potterie, B., 2009. A policy insight into the R&D–patent relationship. *Research Policy*, 38(5), pp.779-792.

Eaton, J. and Kortum, S., 1999. International technology diffusion: theory and measurement. *International Economic Review*, 40(3), pp.537-570.

Falk, M., 2006. What drives business research and development (R&D) intensity across Organisation for Economic Co-operation and

Development (OECD) countries? *Applied Economics*, 38(5), pp.533-547.

Falk, M., 2007. R&D spending in the high-tech sector and economic growth*. Research in Economics*, 61(3), pp.140-147.

Frantzen, D., 2003. The causality between R&D and productivity in manufacturing: An international disaggregate panel data study. *International Review of Applied Economics*, 17(2), pp.125-146.

Fraumeni, B.M. and Okubo, S., 2002. R&D in the national income and product accounts: A first look at its effect on GDP. *Bureau of Economic Analysis Working Papers*, 2002-1.

Freeman, C., 1994. The economics of technical change. *Cambridge Journal of Economics*, 18(5), pp.463-514.

Freeman, C., Clark, J., and Soete, L., 1982. *Unemployment and technical innovation: A study of long waves and economic development.* London: Pinter.

Ginarte, J.C. and Park, W.G., 1997. Determinants of patent rights: A cross-national study. *Research Policy*, 26(3), pp.283-301

Gittleman, M. and Wolff, E.N., 2001. R&D activity and economic development. *International Journal of Public Administration*, 24(10), pp.1061-1081.

Griffith, R., Redding, S., and Van Reenen, J., 2004. Mapping the two faces of R&D: Productivity growth in a panel of OECD countries. *Review of Economics and Statistics*, 86(4), pp.883-895.

Griliches, Z., 1986. Productivity, R&D and basic research at the firm level in the 1970s. *American Economic Review*, 76(1), pp.141-154.

Griliches, Z. and Lichtenberg, F., 1984. Interindustry technology flows and productivity growth: A re-examination. *The Review of Economics and Statistics*, 66 (2), pp.653-659.

Griliches, Z. and Mairesse, J., 1984. Productivity and R&D at the firm level. In: Z. Griliches, ed*. R&D, Patents and Productivity*. Chicago: University of Chicago Press, pp.339-373.

Guellec, D. and van Pottelsberghe de la Potterie, B., 2001. The internationalisation of technology analysed with patent data. *Research Policy*, 30(8), pp.1256-1266.

Guellec, D. and van Pottelsberghe de la Potterie, B., 2004. From R&D to productivity growth: Do the institutional settings and the source of funds of R&D matter? *Oxford Bulletin of Economics and Statistics*, 66(3), pp.353-378.

Hadri, K., 2000. Testing for stationarity in heterogenous panel data. *Econometrics Journal*, 3(2), pp.148-161.

Hasan, I. and Tucci, C.L., 2010.The innovation–economic growth nexus: Global evidence. *Research Policy*, 39(10), pp.1264-1276.

Im, K., Pesaran, M., and Shin, Y., 2003. Testing for unit roots in heterogenous panels. *Journal of Econometrics*, 115(1), pp.53-74.

Jones, C.I., 1995. Time series tests of endogenous growth models. *Quarterly Journal of Economics*, 110(2), pp.495-525.

Kleinknecht, A. and Verspagen, B., 1990. Demand and innovation: Schmookler reexamined. *Research Policy*, 19(4), pp.387-394.

Lach, S. and Schankerman, M., 1989. Dynamics of R&D and physical investment in the scientific sector. *Journal of Political Economy*, 97(4), pp.880-904.

Lanjouw, J. and Schankerman, M., 2004. Patent quality and research productivity: Measuring innovation with multiple indicators. *The Economic Journal*, 114(495), pp.441-465.

LeBel, P., 2008. The role of creative innovation in economic growth: Some international comparisons. *Journal of Asian Economics*, 19(4), pp.334-347

Levin, A., Lin, C., and Chu, J., 2002. Unit root tests in panel data: Asymptotic and finite- sample properties. *Journal of Econometrics*, 108(1), pp.1–24.

Lichtenberg, F.R., 1992. R&D investment and international productivity differences. *NBER Working Paper Series*, 4161.

Lucas, R.E., Jr., 1988. On the mechanics of economic development. *Journal of Monetary Economics*, 22(1), pp.3-42.

Maddala, G., and Wu, S., 1999. A comparative study of unit root tests with panel data and a new simple test. *Oxford Bulletin of Economics and Statistics*, 61, pp. 631-652.

Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Research Policy*, 38(5), pp.700-709

OECD, 1993. *The measurement of scientific and technological activities: Proposed standard practice for surveys of research and experimental development (Frascati Manual).* Paris: OECD.

Pakes, A. and Griliches, Z., 1980. Patents and R&D at the firm level: A first report. *Economic Letters*, 5(4), pp.377-381.

Pesaran, H., 2004. General diagnostic tests for cross section dependence in panels. *Cambridge Working Papers in Economics*, 0435.

Pesaran, H., 2007. A simple panel unit root test in the presence of cross section dependence. *Journal of Applied Econometrics*, 22(2), pp.265-312.

Porter, M.E. and Stern, S., 2000. Measuring the ‘ideas’ production function: Evidence from international patent output. *NBER Working Paper*, 7891.

Ramsey, F., 1928. A mathematical theory of saving. *Economic Journal*, 38(152), pp.543-559.

Romer, P.M., 1986. Increasing returns and long run growth. *Journal of Political Economy*, 94(5), pp.1002-1037.

Scherer, F.M., 1982. Inter-industry technology flows and productivity growth. *The Review of Economics and Statistics*, 64(4), pp.627-634.

Schmookler, J., 1966. *Invention and economic growth*. Cambridge, MA: Harvard University Press.

Schumpeter, J., 1975. *Capitalism, socialism and democracy*. New York: Harper.

Solow, R.M., 1956. A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70(1), pp.65-94.

Stiglitz, J.E., 1993. Endogenous growth cycles. *NBER Working Paper,* 4283.

Stoneman, P., 1979. Patenting activity: A re-evaluation of the influence of demand pressures. *Journal of Industrial Economics*, 27(4), pp.385-401.

Swan, T.W., 1956. Economic growth and capital accumulation. *Economic Record*, 32(2), pp.334-361.

Teitel, S., 1994. Patents, R&D expenditures, country size, and per-capita income: An international comparison. *Scientometrics,* 29(1), pp.137-159.

Trott, P., 2005. *Innovation management and new product development*. 3rd edition. England: Pearson Education Limited.

Ulku, H., 2004. R&D, innovation, and economic growth: An empirical analysis. *IMF Working Paper*, 04/185.

Usher, A.P., 1954. *A history of mechanical inventions*. New York: Dover Publications.

van Pottelsberghe de la Potterie, B., 1997. Issues in assessing the effect of interindustry R&D spillovers. *Economic Systems Research*, 9(4), pp.331-356.

Walsh, V., 1984. Invention and innovation in the chemical-industry: Demand-pull or discovery-push? *Research Policy*, 13(4), pp.211-234.

Wakelin, K., 2001. Productivity growth and R&D expenditure in UK manufacturing firms*. Research Policy*, 30(7), pp.1079-1090.

Wang, E., 2010. Determinants of R&D investment: The extreme-bounds-analysis approach applied to 26 OECD countries. *Research Policy*, 39(1), pp.103-116.

Wyatt, G., 1986. *The economics of invention*. New York: St Martin’s Press.

Zachariadis, M., 2003. R&D, innovation, and technological progress: A test of the Schumpeterian framework without scale effects. *Canadian Journal of Economics*, 36(3), pp.566-686.