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Article

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ABSTRACT

This paper presents new estimates for 21 OECD countries covering the period 1960-2001, focusing on two questions: To what extent does the impact of public capital on output differ across countries? And to what extent does it differ over time? Using vector autoregressions (VARs), we find that in some countries a shock to public capital has a positive long-run impact on GDP while in others the long-run impact is zero or even negative. We also find that variability of public capital and its long-run impact on output are negatively correlated. Furthermore, when the public capital stock is large relative to the private capital stock the long-run impact of public capital is lower. Our results on 'recursive' VARs suggest that in the majority of countries the effect of a public-capital shock on output has decreased over time. Countries where the impact of public capital decreased during the 1990s have a declining public-capital-to-GDP ratio, and vice versa. Estimates based on a panel VAR for the OECD area confirm the declining long-run impact of public capital.

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Time-varying impact of public capital on output: New evidence based on VARs for OECD countries

1. Introduction

It is hard to imagine a well-functioning economy without public capital. While public capital is necessary for modern economies to function, it may not be the case that more public capital causes more growth at all stages of development. Indeed, in their survey Romp and De Haan (2005) report that even though the findings of recent studies on the impact of public capital on output are less dispersed than those of older studies, there is still quite some variety in the findings, particularly as to the magnitude of the effect. In other words, the literature supports the notion that public capital matters but it cannot serve to unequivocally argue in favour of more or less public investment (Estache and Fay 2007).

The variety of findings is, in fact, unsurprising. There is no reason to expect the effect of public capital to be constant (or even systematically positive) over time or across countries. Furthermore, estimating the impact of public capital on output is a complicated endeavour, and papers vary in how carefully they deal with pitfalls, like endogeneity and lack of sufficiently long time series of high-quality data (Estache and Fay 2007).

Various authors have tried to determine the productivity effects of public capital by estimating a Cobb-Douglas production function that includes public capital as an input. Aschauer (1989) was one of the first to use this approach for the United States in an attempt to explain the productivity slowdown of the 1970s. He found that a one-percent increase in the public capital stock increases private capital productivity by 0.39 percent, suggesting that public capital is an important determinant of production. Since then, many authors have employed this approach (see Romp and De Haan 2005). However, while public capital may affect productivity and output, economic growth can also shape the demand and supply of public capital services, which is likely to cause an upward bias in the estimated returns to public capital.

To deal with the interaction between output, public capital, and private capital, Vector Auto Regression (VAR) models have been proposed. The VAR approach sidesteps the need to specify a structural model by modelling every endogenous variable as a function of its own lagged values and the lagged values of the other variables in the system. VAR models have a number of advantages over structural approaches such as the production function approach (Kamps 2004). First, VAR models do not impose any causal links between the variables *a priori* but allow testing whether the causal relationship implied by the production function approach is valid or whether there are feedback effects from output to inputs. Second, the VAR approach allows for indirect links between the variables in the model. In the VAR approach, the long-run output effect of a change in public capital results from the interaction of all the variables in the model. For example, public capital may not only directly affect output but may also have an indirect impact on output *via* its effects on the private factors of production. Third, the VAR approach does not assume that there is at most one long-run relationship among the variables in the model.

This paper first offers a survey of recent research on the impact of public capital on output in which VAR models are used. After identifying the major steps that have to be taken in deciding on the specification of a VAR, we come up with new estimates for 21 OECD countries covering the period 1960-2001. We focus on two important questions. First, to what extent does the impact of public capital differ across countries? Second, to what extent does it differ over time?



Richard Jong-A-Pin



Jakob de Haan

In some countries a shock to public capital has a positive long-run impact on GDP, in others the impact is zero or even negative.

We apply two approaches in this paper. The first approach is based on the work by Kamps (2004) who estimates VAR models for individual OECD countries. Our analysis differs from Kamps (2004) as we do not use employment as our measure for labour input but the number of hours worked. It turns out that this choice leads to rather different results than those reported by Kamps (2004). While in some countries a shock to public capital has a positive long-run impact on GDP, in others the long-run impact is zero or even negative. We find no evidence of a systematic relationship between the size of the capital stock (relative to GDP) and the long-run impact of public capital in a cross-section of OECD countries. However, we do find a negative relationship between the ratio of public capital to private capital and the estimated long-run impact of public capital. Moreover, we find that the variability of the public capital stock and the estimated long-run impact of public capital on output are negatively correlated.

Using so-called 'recursive VARs', in which the period of estimation is increased by one year in every new regression, we examine whether the impact of public capital on output has changed over time. It turns out that for many countries the relationship is not constant. Three groups can be distinguished: In some countries the effect of public capital has increased, in some others it has been relatively stable, but in the majority of countries the effect of a public-capital shock on output has decreased over time. We find that these trends depend on the change in the public capital stock. That is, countries where the impact of public capital on output increased during the 1990s have an increasing public-capital-to-GDP ratio, while countries with a negative trend in the long-run impact of public capital on output saw this ratio decline.

The second approach that we apply is a panel VAR model. An important motivation is the relatively short time span covered by the data for individual countries. The outcomes of VARs are known to be less reliable if based on short time series. Although we use the most comprehensive data set currently available, the period covered by these data may still be too short. The results of the VAR models estimated at the country level should therefore be treated carefully. As an alternative, we also estimate a panel VAR model, which better allows addressing our second research question, *i.e.*, whether there is a time-varying effect of public capital on output. For this purpose we estimate a 'rolling' panel VAR and find that the long-run impact of public capital on output has clearly declined over time.

The remainder of the paper is structured as follows. Section 2 summarizes recent VAR studies on the relationship between public capital (or public investment) and economic growth. Section 3 presents our estimates of a similar model as that of Kamps (2004), while Section 4 contains the 'recursive VARs' and the estimation results for the panel VAR. Section 5 offers some concluding comments.

2. Using VARs to examine the impact of public capital on economic growth

A vector autoregression is modelled as:¹

$$(1) \quad z_t = A(L)z_t + u_t$$

where z_t is a vector of endogenous variables, $A(L)$ is a matrix of polynomial order p , and u_t is a vector of reduced form errors. Before one is able to estimate a VAR model to analyse the impact of public capital on output, various choices need to be made. First, what is the sample period under consideration? Second, which variable will be used for public capital? Third, which other variables

¹ For simplicity of exposition we only show endogenous variables in the equations.

will be included? Fourth, how should the model be estimated? Fifth, how many lags should be included? Sixth, how should the model be identified? And finally, how to calculate the impact of public capital on output?

With respect to the choice of the sample period, there is a trade-off: The longer the sample period is, the more degrees of freedom are available for estimation, but the larger the probability that the parameters will not be constant. More degrees of freedom can be gained by employing higher frequency data, but many series – notably government capital – are only available at an annual frequency.

Many studies use the stock of public capital. In calculating the stock of public capital on the basis of investment flow data, researchers typically use the sum of the monetary value of past investment, adjusted for depreciation. In applying the so-called perpetual inventory method, the researcher has to make certain assumptions about the assets' lifespan and depreciation. Furthermore, one needs an initial level for the capital stock. Especially with infrastructure these assumptions are far from trivial. There is huge variation in the economic lifespan of different types of infrastructure; the lifespan of a railroad bridge cannot be compared with the lifespan of an electricity line. Usually, the initial stock is calculated by assuming that real investment prior to the sample period was constant at the level for the first observation and that the capital stock was at its steady state at the start of the sample period. With low depreciation rates, the rate of convergence towards the steady state level is low, which requires a long time of constant investment.

As to the number of variables in a VAR model there is a limit: The larger and more complicated a VAR model becomes, the more parameters in the $A(L)$ matrices need to be estimated and the more degrees of freedom are used. Hence, there is a trade-off between rich information set for modelling the impact of public capital on economic growth and over-parameterisation of the econometric model.

Estimation of the unrestricted VAR model is easy. The equations of the VAR can be estimated separately by ordinary least squares (OLS). Under general conditions, the OLS estimator of A is consistent and asymptotically normally distributed. This result not only holds in the case of stationary variables but also when some variables are integrated and possibly cointegrated (Sims *et al.* 1990). As pointed out by Kamps (2004), various older studies have ignored non-stationarity issues and estimated unrestricted VAR models in levels based on this result. However, Phillips (1998) showed that impulse responses and forecast error variance decompositions based on the estimation of unrestricted VAR models are inconsistent at long horizons in the presence of non-stationary variables. As impulse response analysis is one of the main tools for policy analysis based on VAR models, a careful investigation of the integration and cointegration properties of the VAR system is warranted. Hence, one has to test for the existence, and number, of cointegrating vectors. Many authors have used the Engle-Granger cointegration test for this purpose. However, this test assumes that there is only one cointegrating vector. Furthermore, as it is a Dickey-Fuller test on the residuals of the estimated equation, the low power of this test in small samples is also problematic. As a consequence, the Engle-Granger test may be unable to detect cointegration when it is present in the data (see Kremers *et al.* 1992). Therefore, the approach suggested by Johansen (1988) has often been used.²

Infrastructure assets' lifespan and depreciation vary a great deal.

² This approach is more vulnerable than the Engle-Granger procedure to the small sample bias toward finding cointegration when it does not exist. This holds especially when variables have long term memory and trending behaviour (Gonzalo and Lee 1998).

This consists of estimating:

$$(2) \quad \Delta z_t = c + \Gamma(L)\Delta z_t + \Pi z_{t-1} + \varepsilon_t$$

and using the trace test and/or the maximum eigenvalue test to determine the number of cointegrating vectors. The cointegration rank, *i.e.*, the rank $(\Pi) = r$, determines whether or not cointegration is present. In case of four variables, there is cointegration if $0 < r < 4$. Johansen (1988; 1991) suggests two possibilities to determine the number of cointegrating vectors: The trace test tests the null hypothesis of r cointegrating relations against the alternative of more than r cointegrating relations, while in the maximum eigenvalue test the null hypothesis of r cointegrating relations is tested against the alternative of $r+1$ cointegrating relations.

The analysis accounts for long-run relationships and short-run dynamics.

A vector error correction model (VECM) is a restricted VAR model that can capture restrictions implied by theory. The VECM has cointegration relations built into the specification so that it restricts the long-run behaviour of the endogenous variables to converge to their cointegrating relationships, while allowing for short-run adjustment dynamics. The cointegration term is known as the error correction term since the deviation from the long-run equilibrium is corrected gradually through a series of partial short-run adjustments. To take the simplest possible example, consider two variables x and y with one cointegrating equation, *i.e.*, $y_t = \beta x_t$, and no lagged difference terms. The corresponding VECM is:

$$(3) \quad \begin{aligned} \Delta x_t &= \alpha_1(y_{t-1} - \beta x_t) + \varepsilon_{1,t} \\ \Delta y_t &= \alpha_2(y_{t-1} - \beta x_t) + \varepsilon_{2,t} \end{aligned}$$

In this simple model, the only right-hand side variable is the error correction term. In long-run equilibrium, this term is zero. However, if x and y deviate from this long-run equilibrium, the error correction term will be nonzero and each variable adjusts to partially restore the equilibrium relation. The α -coefficients measure the speed of adjustment towards the equilibrium.

After estimating a VAR model (or VECM) we would like to be able to discuss the impact of changes in one variable on another. A shock to the i -th variable not only directly affects the i -th variable, but is also transmitted to all other endogenous variables through the dynamic (lag) structure of the VAR. An impulse response function traces the effect of a one-time shock to one of the variables on current and future values of the endogenous variables. We cannot, however, simply change one of the elements of u_t in equation (1) and see what happens because the errors in u_t are correlated with each other. In order to interpret the impulses, it is common to apply a transformation to the innovations so that they become uncorrelated, thereby enabling identification of the model. One of the most commonly used identification strategies is the Cholesky decomposition. The Cholesky decomposition is a simple algorithm for splitting a positive-definite matrix into a triangular matrix times its transpose.³ The ease of implementation explains why it is so widely used. However, the impulse response functions based on the Cholesky decomposition are known to be sensitive to the ordering of variables. The method of Generalized Impulses as described by Pesaran and Shin (1998) constructs an orthogonal set of innovations that does not depend on the VAR ordering. The generalized impulse responses from an innovation to the i -th variable are derived by applying a variable-specific Cholesky factor computed with the i -th variable at the top of the Cholesky ordering.

3 The Cholesky decomposition may appear to be a-theoretical, but it implies a strict causal ordering of the variables in the VAR: The variable positioned last responds contemporaneously to all of the others but has no contemporaneous effect on them; the next to last variable responds contemporaneously to all variables except the last, whilst affecting only the last variable contemporaneously, and so on. The first variable contemporaneously affects all the other variables while not responding contemporaneously to any of them.

Some recent empirical studies that use the VAR methodology to examine the relationship between public capital and economic growth are summarized in Table 1 (see Kamps 2004 for a survey of older studies).

As pointed out by Kamps (2004), only few studies analyse a group of OECD countries. Also, most studies rely on annual data, as capital stock data are often not available at higher frequency. The majority of studies use a model with four variables, namely public capital, private capital, employment and output. In some studies investment has been substituted for capital or additional variables have been included in the model. Apart from theoretical reasons (for instance, the production function approach *versus* a growth model), the order of integration of the series can be a reason to use either the (log of) the capital stock or the (log of) investment.

The results of unit root tests point in different directions. Whereas many studies suggest that all variables usually included – *i.e.*, the log of output, employment, private capital, and public capital – are non-stationary I(1) series (*i.e.*, series integrated of order one), some studies (for instance, Pereira 2000) report that the log of private and public investment are non-stationary I(1) series. In view of the low power of the Dickey-Fuller test for relatively short time series, it is quite remarkable that almost all papers do not use other tests for stationarity.

In various papers, notably in the work by Pereira, it is found that output, employment, and private and public capital stocks (or investment) are not cointegrated. Pereira and his co-authors therefore employ the growth rates of the variables included in the VAR. For the case of Portugal, Pereira and Andr az (2005, p. 181-182) argue that “the absence of cointegration is not problematic conceptually either. In fact, in the case of economies in a transition stage of their development, such as the Portuguese economy, not finding cointegration is hardly surprising. This means that the data does not show evidence of convergence to the so-called great ratios among the aggregate variables in the economy.” However, the question is whether there is really no cointegration, or whether the finding is just a reflection of the testing procedure followed. As follows from Table 1, the conclusion of Pereira and his co-authors is always based on the Engle-Granger test for cointegration. Ligthart (2002) employs both the Engle-Granger test and the Johansen tests and finds that the tests yield different outcomes. Under the Engle-Granger test, the null hypothesis of no cointegration cannot be rejected, while the Johansen tests strongly reject the hypothesis of no cointegration in favour of at least one cointegrating relationship. In addition, Pina and St. Aubyn (2005) also report evidence of a cointegrating relationship for the case of Portugal using the Johansen tests.

Some other studies have found no long-run relationship between output, employment, and private and public capital.

3. New evidence on the impact of public capital on output using VARs

The most extensive study on the impact of public capital on output in which VARs are used is the study of Kamps (2004). This author has made a comparable data set for 22 OECD countries for the public and private capital stock, using the perpetual inventory method (Kamps, 2006).⁴ The data set covers the period 1960-2001. Figure 1 presents the government-capital-stock-to-GDP ratio and the private-capital-stock-to-GDP ratio for the beginning and the end of this period. It becomes clear that there is quite some variation across the countries in the sample, both with respect to the level of the government capital stock ratio and the change of this ratio. In 2001, Japan has the highest, while Ireland has the lowest government capital ratio. In 13 countries the government capital ratio declined, while in nine it increased between 1960 and 2001. The private capital stock ratio also differs considerably among the OECD countries, both with respect to the level and its change over time.

⁴ Available at: <http://www.uni-kiel.de/ifw/forschung/netcap/netcap.htm>.

Table 1. Some VAR studies (published since 2000) on the relationship between public capital and economic growth

Study	Sample/period	Public capital	Theory	Other variables (apart from output)
Pereira (2000)	USA 1956-1977 (A)	Aggregate public investment and 5 types (in constant prices)	--	Employment, private investment
Mittnik and Neumann (2001)	Canada, France, UK, Japan, The Netherlands and Germany Different samples (Q)	Public investment	Barro (1990) and Devajaran <i>et al.</i> (1996)	Private investment, public consumption
Pereira (2001)	USA, 1956-1977 (A)	Aggregate public investment and 5 types (in constant prices)	--	Employment, 7 different types of private investment
Pereira and Roca-Sagales (2001)	Spain 1970-1993 (A)	Stock of infrastructures in transport and communications (in constant prices)	--	Employment, private capital stock
Ligthart (2002)	Portugal 1965-1995 (A)	Public capital stock (in constant prices)	Production function	Labour, private capital
Voss (2002)	US and Canada 1947.I-1998.I 1947.I-1996.IV (Q)	Investment scaled by output	Neo-classical theories of investment	Relative price of public and private investment goods, real interest rate, private investment
Pereira and Roca-Sagales (2003)	Spain and 17 regions in Spain, 1970-95 (A)	Public capital (in constant prices)	--	Employment, private capital stock
Kamps (2004)	22 OECD countries (A)	Public capital stock	Production function	Labour, private capital
Pina and St. Aubyn (2005)	Portugal 1960-2001 (A)	Public capital stock	Production function	Labour, private capital, human capital
Pereira and Andraz (2005)	Portugal 1976-1998 (A)	Public transportation infrastructure investment and 6 types of investment (in constant prices)	--	Employment, private investment
Bello and Vertova (2006)	7 developing countries different samples (A)	Public investment	--	Private investment
Creel and Poilon (2006)	5 OECD countries 1960-2004 (A)	Public investment and public capital stock	Demand effects and production function	Employment, private investment/capital

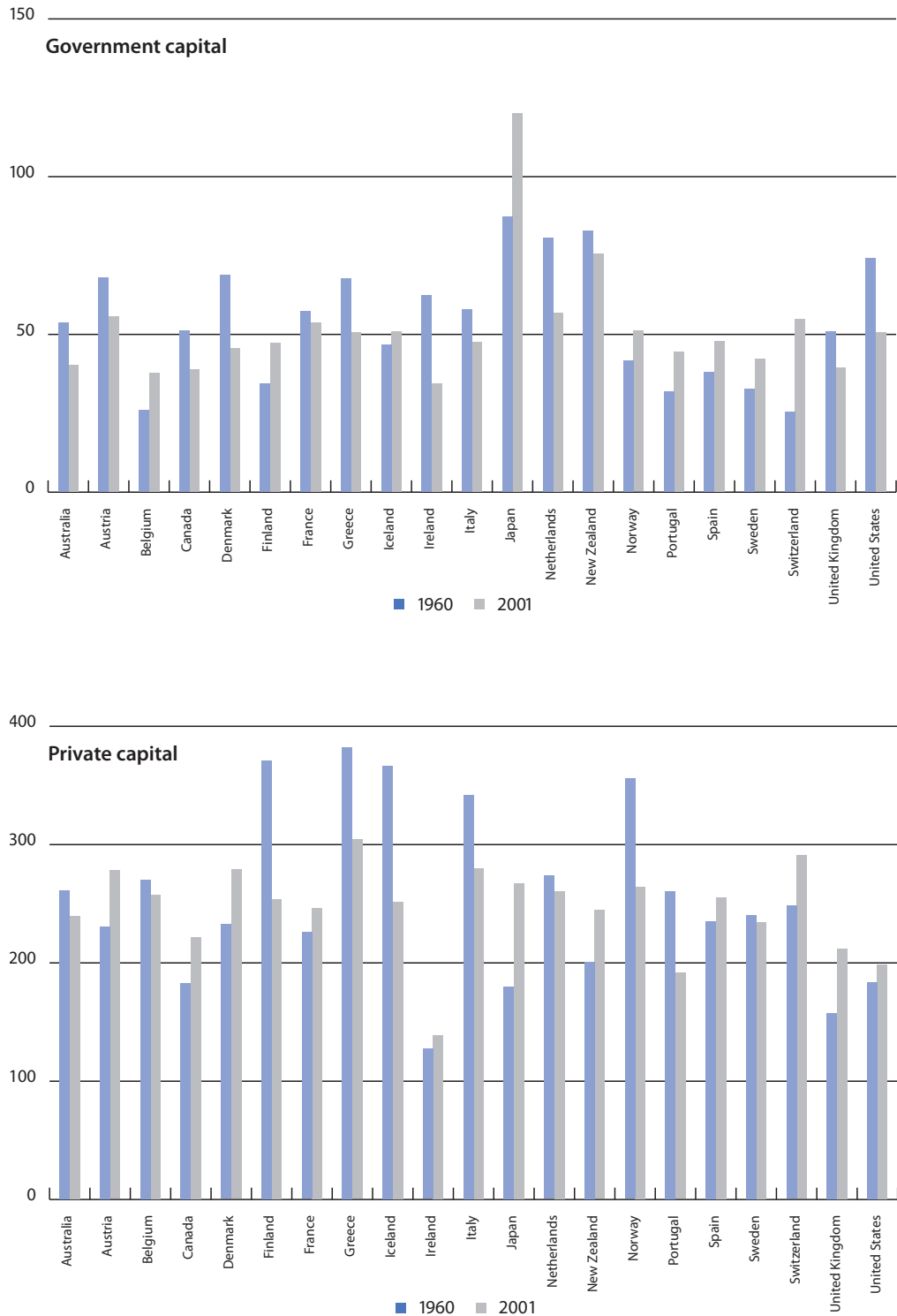
Note: A: annual data; Q: quarterly data; DF: Dickey-Fuller; EG: Engle-Granger; PP: Phillips-Perron.

Stationarity / cointegration test	Stationarity / cointegration results	Specification of output and public capital	Identification	Results
DF unit root test; EG cointegration test	Log of variables are I(1); no cointegration	Growth rate of output and growth rate of investment	Policy function (equivalent to Cholesky decomposition assuming that innovations in public inv. lead innovations in private variables)	Elasticity is 0.043 for aggregate public investment; rate of return 7.8 percent
PP and DF tests; Johansen cointegration test	Series are I(1); r varies between 0 (France, UK) and 3 (Canada)	Log of output and log of investment	Policymakers are assumed to know realizations and announce plans that private sector takes into account; private inv. simultaneously affects GDP, but not vice versa.	Elasticity no more than 0.1 and only significant for Netherlands and Germany
DF unit root test; EG cointegration test	Log of variables are I(1); no cointegration	Growth rate of output and growth rate of investment	Innovations in public investment lead private sector variables	Elasticity is 0.043 for aggregate public investment; rate of return 7.8 percent
DF unit root test; EG cointegration test	Log of variables are I(1); no cointegration	Growth rate of output and growth rate of capital stock	Cholesky where public capital leads private variables	Elasticity is 0.52
DF unit root test; EG and Johansen cointegration tests	Log of variables are I(1); 1 cointegrating vector	Log of level of output and log of level of capital stock	Cholesky	Elasticity between 0.20-0.35
No testing	--	Growth rate of output and level of investment scaled by output	Specific ordering imposed starting with output growth and ending with private investment ratio	Innovations to public investment crowd out private investment
DF unit root test; No cointegration test	Log of variables are I(1)	Growth rate of output and growth rate of capital stock	Policy function (equivalent to Cholesky decomposition assuming that innovations in public inv. lead innovations in private variables)	Aggregate elasticity is 0.523; rate of return 5.5 percent.
Johansen cointegration test	Variables cointegrated with two or three cointegrating vectors	Level of stock	Cholesky	For most countries there is a positive output effect.
Johansen cointegration test	Variables are cointegrated with one cointegrating vector	Level of stock	Cholesky	Returns between 26.7 and 37.3 percent
DF unit root test; EG cointegration test	First difference of log is stationary; No cointegration	Growth rate of output and growth rate of investment	Policy function in which information set includes past values of other variables	Elasticity of output to aggregate investment is 0.183
DF and PP unit root tests; EG and Johansen cointegration tests	First difference of log of variables are stationary; variables are cointegrated	Growth rate of output and growth rate of investment	Various Cholesky orderings in VECM	Positive output elasticities except for Malawi
No testing	--	Level of GDP, investment and stock	Various orderings	In aggregate demand framework short-lived impact; divers results for capital

The ratio of private capital to GDP declined in half of the sample during 1960-2001.

In 2001, Greece had the highest private capital ratio while Ireland had the lowest ratio. In half of the countries the private capital ratio declined, while in the other half the ratio increased during the period under consideration.

Figure 1. Government and private capital relative to GDP in percent, 1960-2001



Source: Data from Kamps (2006)

In contrast to most other studies, we use hours worked and not the number of employees as a measure of labour input.

Also in terms of using adequate econometric methods, the study by Kamps (2004) is by far the best in this line of research. Therefore, we take this study as our starting point, using the same public and private capital stock data and a similar method. However, in contrast to Kamps (2004) and most other studies, we use hours worked as the indicator of labour input. For various reasons this is a better proxy than the number of employees. First, employees may work different hours. Furthermore, in many countries hours worked per employee have decreased over time. As a consequence, the number of hours worked and the number of employees may have a low correlation, as shown in Table 2. The data on hours worked and GDP are from the Total Economy Database of the Groningen Growth and Development Centre.⁵

Table 2. Correlation of number of employees and number of hours worked, 1960-2001

France	-0.71	Ireland	0.73
Denmark	-0.56	Greece	0.76
Belgium	-0.25	Netherlands	0.76
United Kingdom	-0.09	Switzerland	0.78
Austria	-0.05	Japan	0.91
Italy	-0.02	Portugal	0.96
Sweden	0.06	Iceland	0.98
Norway	0.55	United States	0.99
Finland	0.67	New Zealand	1.00
Spain	0.68	Canada	1.00
Germany	0.70	Australia	1.00

Source: Own calculations based on data provided by Groningen Growth and Development Centre

Table 3 shows the results for the unit root tests of the variables we use. We apply the ADF test that states “presence of a unit root” as the null hypothesis, and the KPSS test by Kwiatkowski *et al.* (1992) that has stationarity as the null; in both tests a constant and a trend are included in the test equations. It follows from Table 3 that most variables are integrated of order one.⁶ We therefore proceed by testing for all countries whether the series concerned are cointegrated following the approach suggested by Johansen (1991).

For each country⁷ we specify a four-variable VAR model including the public net capital stock, the private net capital stock, the number of hours worked, and real GDP. Following Kamps (2004), the number of lags to be included has been chosen on the basis of the Schwarz (1978) information criterion.⁸ Table 4 shows the outcomes of the maximum eigenvalue test for cointegration.⁹ The table shows the probability that the null-hypothesis is true. It is assumed that the cointegrating vector(s) and the VAR include a constant. For those countries that have one or more trend stationary variables, the cointegrating vector also includes a trend. A robustness check, in which it is assumed that all series contain a unit root, does not alter the choice of the appropriate number of cointegrating vectors.

5 See www.ggdc.nl. Kamps (2004) used OECD data for GDP and therefore had various missing observations.

6 The hypothesis that the capital stocks are I(2) is clearly rejected.

7 Germany was dropped because data revisions in 1990 made it impossible to estimate a sensible model.

8 When for a given lag structure there is still residual autocorrelation in the model we increase the number of lags (up to a maximum of three) until there is no autocorrelation left in the residuals.

9 The trace statistic and the maximum eigenvalue statistic sometimes yield conflicting results. Following Johansen and Juselius (1990), we examine the estimated cointegrating vector and base our choice on the interpretability of the cointegrating relations.

Table 3. Unit root tests

Country	Series	ADF	KPSS	Unit root	Country	Series	ADF	KPSS	Unit root
Australia	government capital	0.208	0.204	yes	Italy	government capital	1.000	0.185	yes
	hours worked	0.054	0.083	mixed		hours worked	0.135	0.191	yes
	private capital	0.799	0.203	yes		private capital	0.717	0.215	yes
	income	0.078	0.203	yes		income	0.476	0.209	yes
Austria	government capital	0.970	0.214	yes	Japan	government capital	0.527	0.207	yes
	hours worked	0.891	0.191	yes		hours worked	0.997	0.167	yes
	private capital	0.626	0.208	yes		private capital	0.955	0.200	yes
	income	0.840	0.188	yes		income	0.630	0.198	yes
Belgium	government capital	0.325	0.197	yes	Netherlands	government capital	0.001	0.206	mixed
	hours worked	0.999	0.208	yes		hours worked	0.935	0.182	yes
	private capital	0.057	0.187	yes		private capital	0.218	0.204	yes
	income	0.447	0.190	yes		income	0.094	0.159	yes
Canada	government capital	0.186	0.190	yes	Norway	government capital	0.713	0.206	yes
	hours worked	0.346	0.191	yes		hours worked	0.230	0.154	yes
	private capital	0.863	0.184	yes		private capital	0.902	0.205	yes
	income	0.319	0.199	yes		income	0.897	0.197	yes
Denmark	government capital	0.000	0.210	mixed	New Zealand	government capital	0.942	0.210	yes
	hours worked	0.931	0.113	mixed		hours worked	0.404	0.142	mixed
	private capital	0.220	0.208	yes		private capital	0.288	0.192	yes
	income	0.194	0.177	yes		income	0.253	0.108	mixed
Finland	government capital	1.000	0.209	yes	Portugal	government capital	0.013	0.087	no
	hours worked	0.024	0.076	no		hours worked	0.130	0.117	mixed
	private capital	0.998	0.206	yes		private capital	0.651	0.199	yes
	income	0.491	0.175	yes		income	0.489	0.185	yes
France	government capital	0.565	0.209	yes	Spain	government capital	0.046	0.103	no
	hours worked	0.512	0.118	mixed		hours worked	0.556	0.114	mixed
	private capital	0.879	0.211	yes		private capital	0.445	0.204	yes
	income	0.201	0.199	yes		income	0.380	0.174	yes
Germany	government capital	0.942	0.207	yes	Sweden	government capital	0.068	0.199	yes
	hours worked	0.793	0.177	yes		hours worked	0.201	0.147	yes
	private capital	0.417	0.147	yes		private capital	0.854	0.209	yes
	income	0.321	0.122	mixed		income	0.214	0.176	yes
Greece	government capital	0.587	0.203	yes	Switzerland	government capital	0.026	0.208	mixed
	hours worked	0.784	0.201	yes		hours worked	0.260	0.128	mixed
	private capital	0.810	0.209	yes		private capital	0.294	0.199	yes
	income	0.233	0.194	yes		income	0.302	0.156	yes
Iceland	government capital	0.521	0.206	yes	UK	government capital	0.113	0.202	yes
	hours worked	0.103	0.060	mixed		hours worked	0.950	0.178	yes
	private capital	0.878	0.202	yes		private capital	0.614	0.201	yes
	income	0.835	0.198	yes		income	0.066	0.086	mixed
Ireland	government capital	0.009	0.209	mixed	US	government capital	0.392	0.104	mixed
	hours worked	1.000	0.183	yes		hours worked	0.003	0.103	no
	private capital	0.206	0.194	yes		private capital	0.494	0.202	yes
	income	1.000	0.132	mixed		income	0.017	0.137	no

Note: The ADF test assumes as null-hypothesis a unit root while the KPSS test assumes stationarity. Both tests contain an intercept and a trend. The figures shown in the ADF and KPSS columns are p-values.

We find one cointegrating vector for most countries. However, for three countries (Australia, Austria, and Denmark) the hypothesis of no cointegrating vector cannot be rejected. For these countries we therefore estimate an unrestricted VAR using the first differences of the included variables to account for their non-stationarity. For the other countries we estimate VECMs, imposing the number of cointegrating vectors as shown in the final column of Table 4.

Table 4. Cointegration tests (unrestricted cointegration rank test)

Country	Hypothesized number of cointegrating equations				
	None	at most 1	at most 2	at most 3	chosen
Australia	0.097	0.207	0.055	0.839	0
Austria	0.121	0.031	0.084	0.021	0
Belgium	0.006	0.057	0.034	0.112	1
Canada	0.001	0.284	0.123	0.002	1
Denmark	0.398	0.153	0.570	0.072	0*
Finland	0.012	0.147	0.461	0.525	1*
France	0.004	0.071	0.058	0.016	1
Greece	0.001	0.021	0.120	0.016	2
Iceland	0.003	0.284	0.285	0.054	1*
Ireland	0.022	0.030	0.012	0.914	3*
Italy	0.040	0.087	0.233	0.042	1
Japan	0.000	0.140	0.077	0.216	1
Netherlands	0.020	0.239	0.320	0.777	1*
New Zealand	0.046	0.072	0.201	0.561	1
Norway	0.001	0.107	0.025	0.088	1
Portugal	0.005	0.200	0.251	0.666	1*
Spain	0.000	0.002	0.050	0.253	3*
Sweden	0.016	0.007	0.259	0.612	2*
Switzerland	0.008	0.118	0.467	0.171	1*
United Kingdom	0.010	0.020	0.419	0.221	2*
United States	0.011	0.054	0.497	0.414	1*

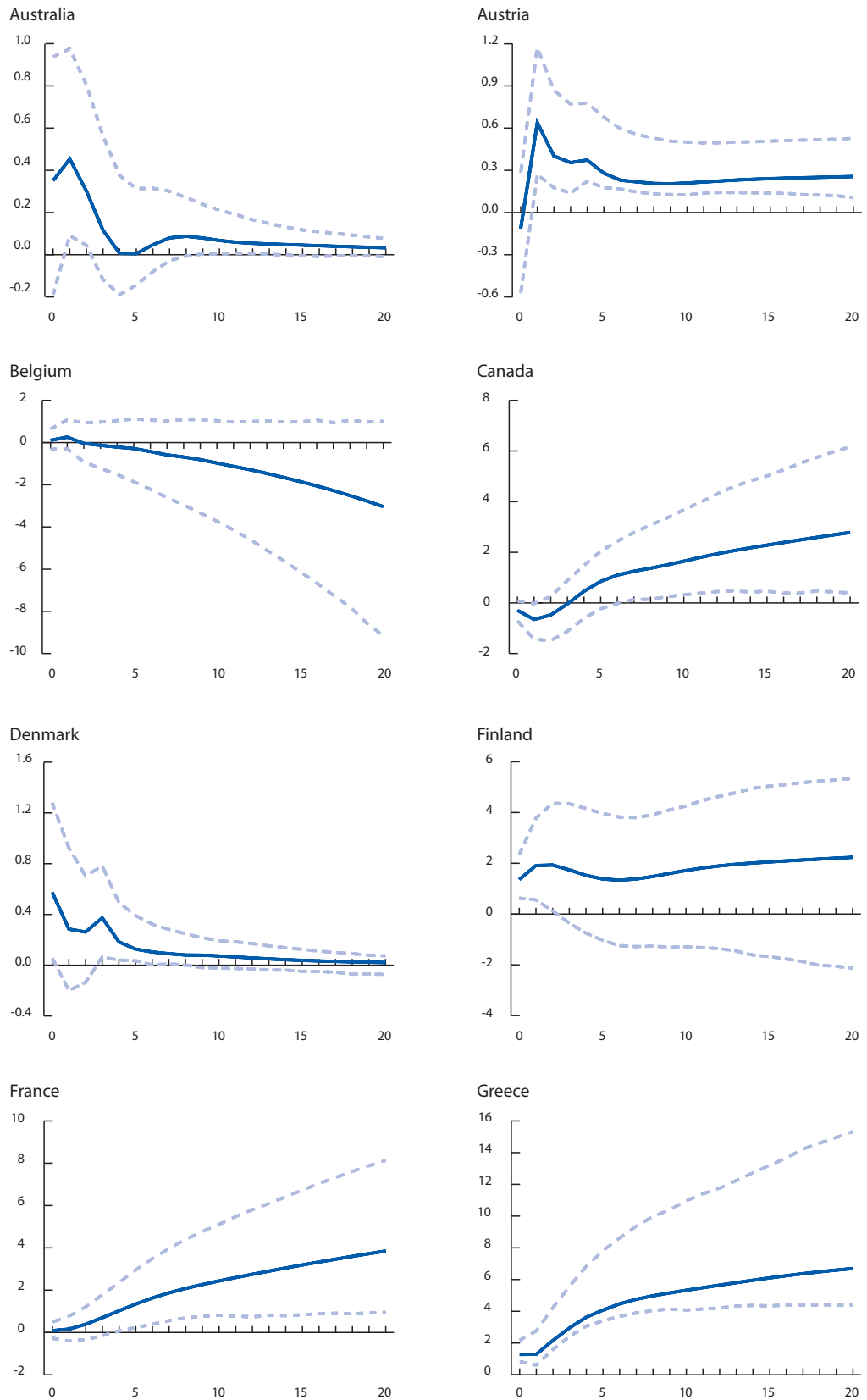
Note: Results for the maximum eigenvalue test. The table shows the probability that the null-hypothesis is true. A * indicates that the trace test yields the same number of cointegrating vectors.

Figure 2 shows the generalized impulse responses to a one standard deviation shock to public capital for a horizon of 20 years. Each graph displays a point estimate of the impulse responses as well as a 90-percent confidence interval computed following the bootstrap procedure suggested by Hall (1988). The shocks to public capital have a different size for each country, thereby precluding a quantitative comparison of the effects across countries. However, as Kamps (2004) points out, shocks of such size have the attractive feature that they can be viewed as representative for typical shocks that occurred during the sample period in the individual countries.

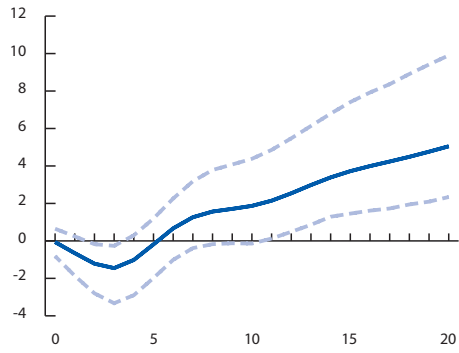
Two important conclusions can be drawn on the basis of the impulse responses. First, for various countries a shock to public capital has a positive long-run impact on GDP (Austria, Canada, France, Greece, Iceland, Norway, Switzerland, and the US). But there are also quite some countries where the long-run impact is essentially zero (Australia, Belgium, Denmark, Finland, Italy, Netherlands, New Zealand, Spain, Sweden, and the UK). For three countries the effect is found to be even negative (Ireland, Japan, and Portugal). Second, our results deviate substantially from those of Kamps (2004), notably for those countries for which the correlation between the number of employees and hours worked is low.

For eight countries a shock to public capital has a positive long-run impact on GDP.

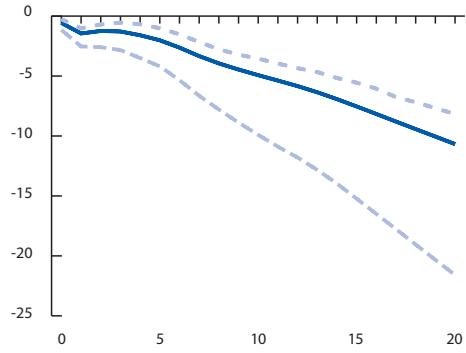
Figure 2. Impulse responses of GDP to a shock in public capital



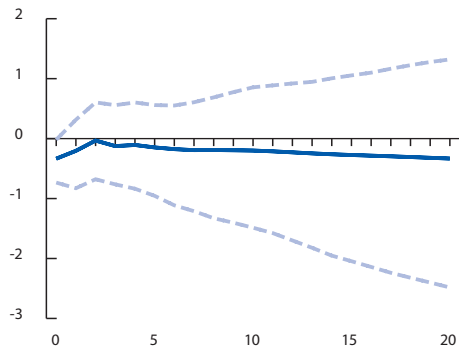
Iceland



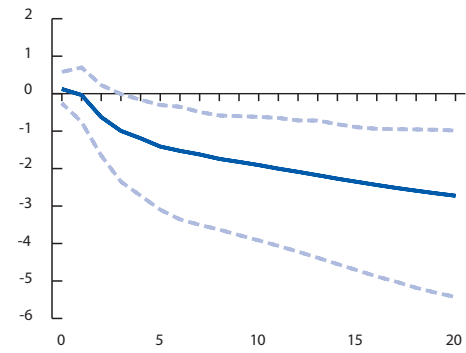
Ireland



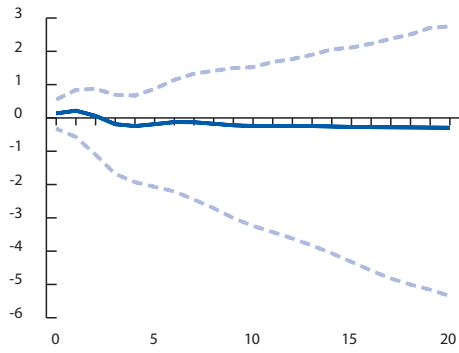
Italy



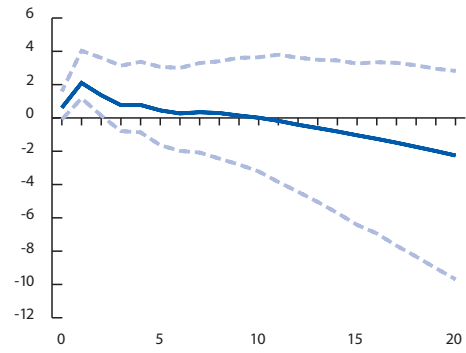
Japan



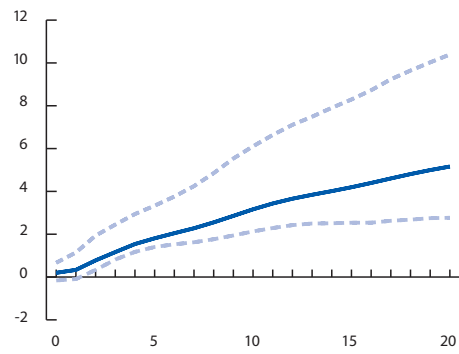
Netherlands



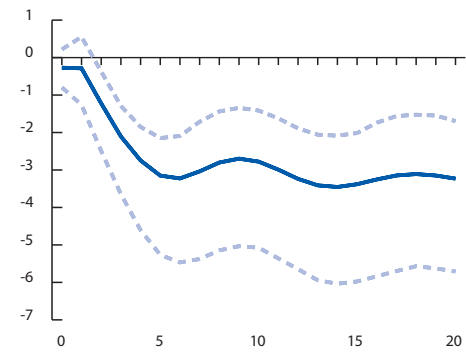
New Zealand

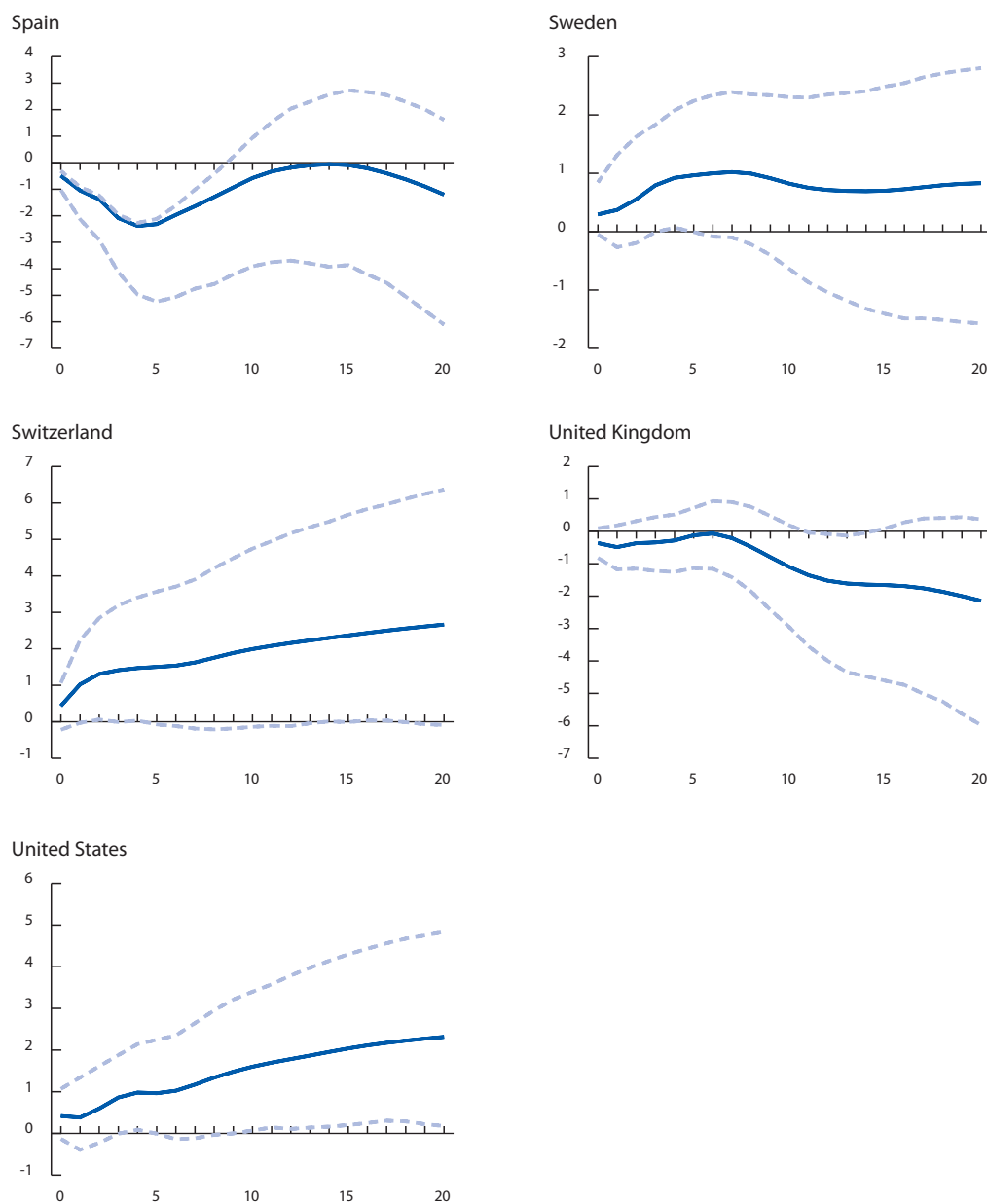


Norway



Portugal





Note: The figures show the impulse response of output to a one-standard-deviation shock to public capital over a period of 20 years.

There is no systematic pattern for the impact of public capital on output.

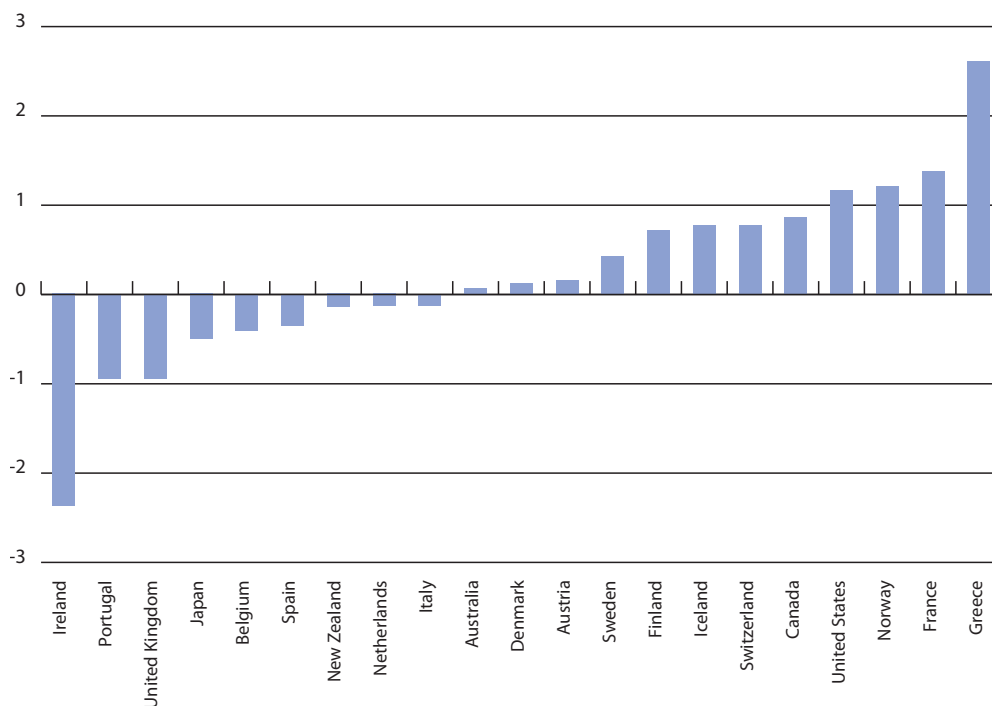
It is hard to draw clear policy conclusions from our findings. There is not a clear systematic pattern for the impact of public capital on output. According to the generalized impulse responses, the long-run impact of public capital on output can be positive, zero, or negative (see Figure 3).¹⁰ We find the strongest negative effect in Ireland and the strongest positive effect in Greece. This diversity in results may not be surprising as the impact of public capital may depend on various factors like the level of the public capital stock. If the public capital stock is very high, there may be

¹⁰ The long run impact is defined as the response after 20 periods (as shown in Figure 2) divided by a one standard-deviation shock in public capital.

diminishing marginal returns. In the remainder of this section we will therefore examine our findings in more detail.

Marginal returns to a very high public capital stock may be diminishing.

Figure 3. Estimated long-run impact of public capital on output



Note: The figure shows (per country) the estimated long run (semi) elasticity of output with respect to public capital calculated as the response after 20 periods (as shown in Figure 2) divided by a one standard-deviation shock in public capital.

We examine whether there is a systematic relationship between our estimates of the long-run effect of public capital on output for the various countries (as shown in Figure 3) and the

- Average of the public-capital-to-GDP ratio;
- Public-capital-to-private-capital ratio;
- Change in the public-capital-to-GDP ratio; and
- Variability in the public-capital-to-GDP ratio

in these countries measured over the same sample as the one used in our VAR estimates.

Figure (4a) suggests that there is a negative relationship between the long-run impact of public capital on output and the level of public capital. The negative slope of the regression line is in accordance with the hypothesis that a higher public capital stock implies a lower impact of public capital on output. However, the relationship is not significant. The estimated t-statistic is 0.94 ($p = 0.359$). In other words, the diversity in our sample with respect to the level of public capital is not related to the diversity in our results for the long-term impact of public capital on output. Countries for which we find a positive impact of public capital on output do not have a lower or higher capital-stock-to-GDP ratio than those with a negative impact of public capital on output.

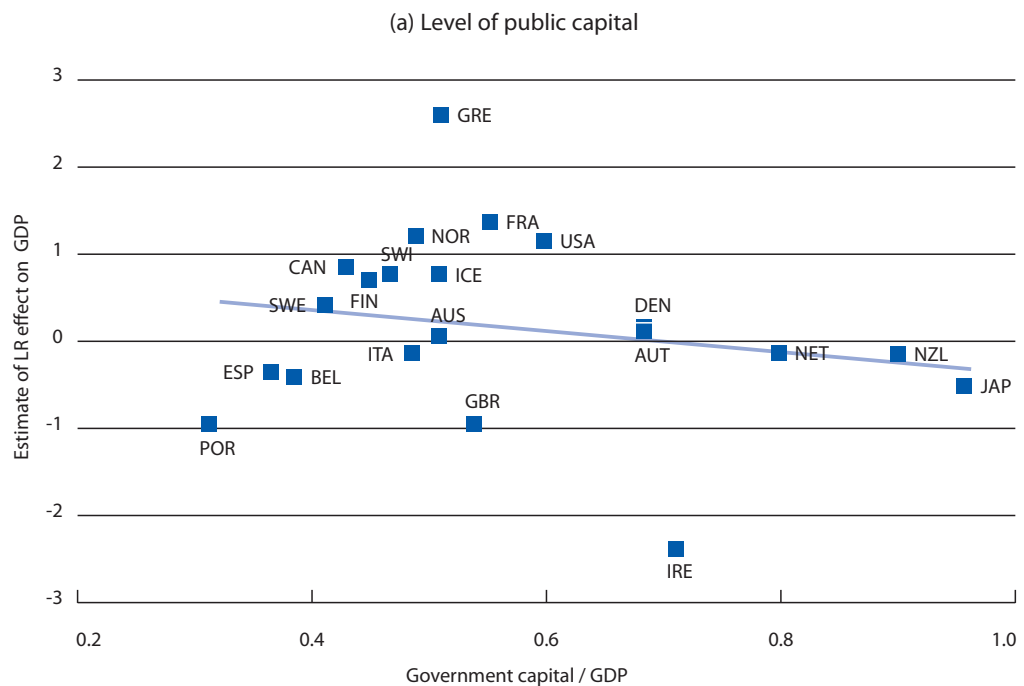
Figure (4b) shows that a high ratio of public capital to private capital is negatively and significantly related to the impact of public capital on output (the t-statistic is 2.22, with $p = 0.038$). Apparently, the impact of public capital does not depend on its absolute level, but on its level relative to private capital. If the public capital stock is large relative to the private capital stock, the long-run impact of public capital on output is lower.

The regression line in Figure (4c) does not yield a significant relationship (the estimated t-statistic is 0.19, with $p = 0.852$). So the diversity in our sample with respect to the change in the public-capital-to-GDP ratio is not related to our results for the long-term impact of public capital on output. In other words, this finding suggests that there is not a systematic difference with respect to the long-run impact of public capital on output between countries that saw their capital-to-GDP ratio decline and those that saw this ratio increase.

High variability of the public-capital stock reduces its long-run impact on output.

Finally, Figure (4d) suggests that there is a negative and significant relationship between the variability of the public capital stock and our findings for the long-term impact of public capital on output. The estimated t-statistic is -2.40 ($p = 0.027$). So these findings suggest that high variability of the public capital stock reduces the long-run impact of public capital on output.¹¹

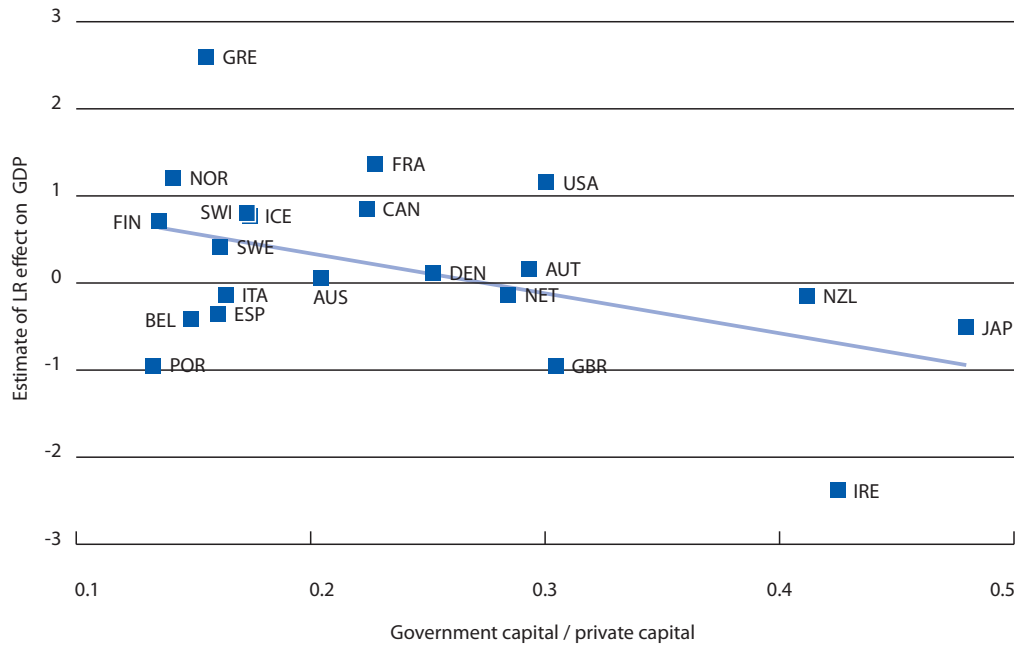
Figure 4. Government capital and its long-run effect on output, 1960-2001



Note: The vertical axis shows the long-run impact on GDP of a shock to public capital, while the horizontal axis shows the average public-capital-to-GDP ratio for the country concerned.

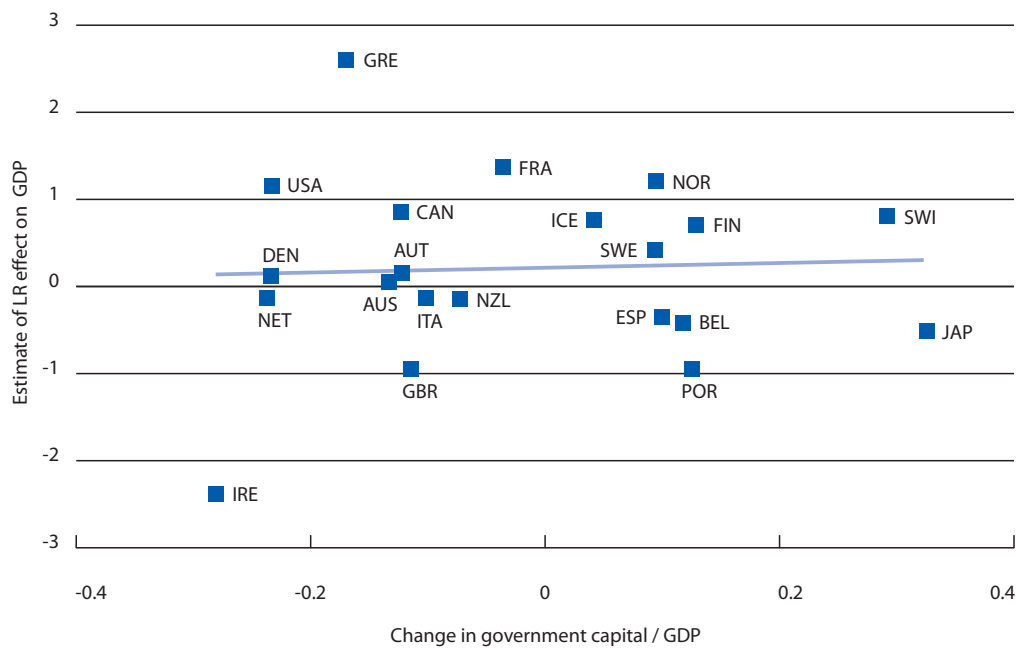
11 In principle, there may be two sources of high standard deviations in the public-capital-to-GDP ratio, (i) public investment being "erratic", and (ii) public investment having a strong trend such that it is very different at the end of the sample from its initial level. As the correlation between the absolute change and the standard deviation of the public-capital-to-GDP ratio is 0.79, we conclude that the variability in the public capital GDP to ratio is largely driven by the second source.

(b) Public-capital-to-private-capital ratio

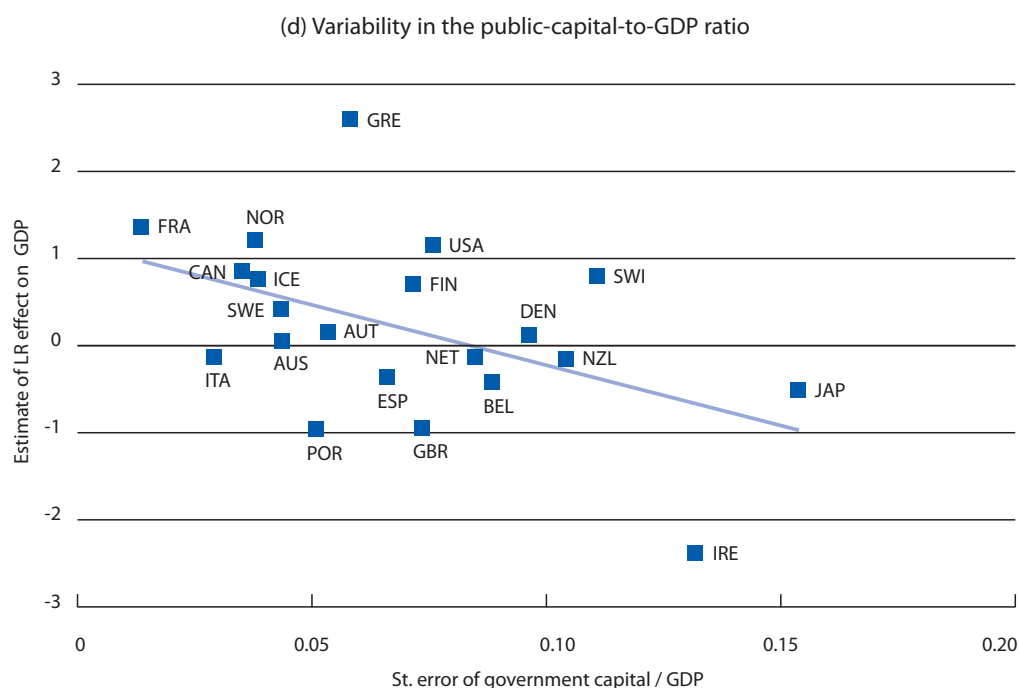


Note: The vertical axis shows the long-run impact on income of a shock to public capital, while the horizontal axis shows the average ratio of the public capital to private capital stock for the country concerned.

(c) Change in the public-capital-to-GDP ratio



Note: The vertical axis shows the long-run impact on income of a shock to public capital, while the horizontal axis shows the change in the public-capital-to-GDP ratio over 1960-2001 for the country concerned.



Note: The vertical axis shows the long-run impact on income of a shock to public capital, while the horizontal axis shows the standard deviation of the public-capital-to-GDP ratio over 1960-2001 for the country concerned.

4. Recursive and panel VARs

In the previous section we have focused on our first research question to see to what extent the impact of public capital differs across countries. In this section we will address our second research question, *i.e.*, to what extent the impact of public capital on output differs over time. To address this issue, we use 'recursive' VARs and 'rolling-window' panel VARs.

4.1 Recursive VARs

Has the impact of public capital on output changed over time?

This subsection reports our findings for so-called 'recursive VARs'. The purpose of this analysis is to examine whether the impact of public capital on output has changed during the 1990s in comparison to the earlier decades. Recursive estimates are done for all countries in our sample starting with the period 1960-1989 up to 1960-2001. So we start with a VAR for the period 1960-89 and then add one year to the estimation period in each step. In all VARs we impose the same number of cointegrating vectors as found for the full sample period. For each regression, the long-run effect (accumulated GDP response relative to a one-standard deviation shock in public capital) is estimated. The estimated long-run effects are shown in Table 5, with significant long-run elasticities shown in italics.

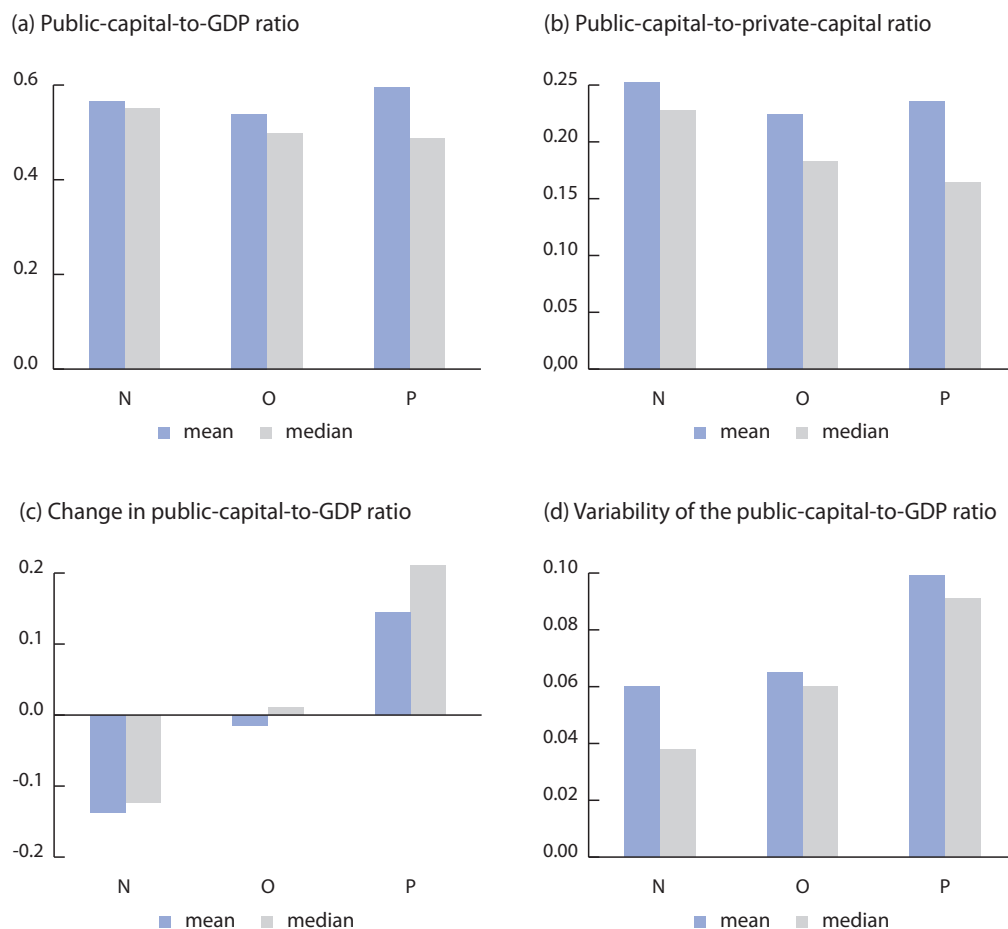
The final column in Table 5 shows the results of a regression of the estimated long-run elasticities on a time trend. We have made three groups of countries, depending on the change in the estimated elasticity over time. In the first group ("P") the estimated coefficient of the trend variable is positive and significant, suggesting that in these countries public capital has become more productive over time. In the second group ("N") the estimated coefficient is negative and significant, suggesting that public capital has become less productive over time. Finally, if the estimated coefficient of the trend variable is insignificant, the country is in the "O" group.

Table 5. Estimated long-run effects of public capital on output: Recursive VARs

Country	60-89	60-90	60-91	60-92	60-93	60-94	60-95	60-96	60-97	60-98	60-99	60-00	60-01	Trend
Australia	0.07	0.05	0.11	0.10	0.10	0.09	0.09	0.08	0.07	0.06	0.06	0.06	0.06	O
Austria	0.13	0.09	0.14	0.14	0.15	0.11	0.11	0.14	0.15	0.24	0.11	0.10	0.15	O
Belgium	-1.07	-1.13	-0.90	0.11	0.54	0.38	-0.02	0.25	-0.08	-0.46	-0.52	-0.65	-0.41	O
Canada	1.94	1.78	1.51	1.60	1.32	1.25	1.07	0.89	0.93	0.91	0.97	0.87	0.85	N
Denmark	0.13	0.15	0.15	0.14	0.13	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.12	N
Finland	-0.09	-0.27	0.16	0.20	0.43	0.24	0.44	0.40	0.53	0.62	0.63	0.62	0.71	P
France	2.58	2.40	2.31	2.22	1.91	1.84	1.79	1.57	1.62	1.48	1.44	1.42	1.37	N
Greece	-7.00	-2.85	2.19	0.87	0.21	0.30	0.87	0.99	1.57	1.31	1.44	2.33	2.60	P
Iceland	2.32	2.07	1.87	1.91	1.65	1.33	1.60	1.22	1.06	1.04	0.84	0.84	0.77	N
Ireland	0.82	0.51	0.78	0.28	-0.18	-0.91	-1.77	-1.79	-2.26	-2.30	-2.64	-2.52	-2.38	N
Italy	0.34	0.22	0.12	0.05	0.04	0.26	-0.17	-0.30	-0.21	-0.17	-0.14	-0.11	-0.13	N
Japan	-1.17	-1.34	-0.87	-0.63	-0.30	-0.30	-0.25	-0.22	-0.41	-0.50	-0.60	-0.54	-0.51	P
Netherlands	3.62	2.39	-0.47	-0.20	-0.12	-0.33	-0.19	-0.24	0.29	0.19	0.10	-0.20	-0.13	O
New Zealand	-4.98	-0.46	1.37	2.12	0.97	-1.36	-3.81	-2.39	-1.72	-0.18	-0.42	-0.41	-0.15	O
Norway	1.07	1.00	0.73	1.20	1.11	2.87	1.84	1.84	1.68	1.73	1.54	1.54	1.21	O
Portugal	-0.99	-0.94	-0.96	-0.73	-1.07	-1.14	-1.21	-1.32	-1.33	-1.20	-1.04	-0.95	-0.95	O
Spain	1.92	-0.31	-0.91	-1.35	-0.92	-0.18	-0.27	-0.42	-0.43	-0.63	-0.72	-0.76	-0.36	O
Sweden	-1.05	-1.36	-0.07	1.01	0.97	0.84	0.17	0.04	-0.01	0.00	0.16	0.49	0.42	O
Switzerland	-0.68	-1.49	-1.21	-0.88	-0.36	-0.26	0.01	0.09	0.22	0.29	0.86	0.70	0.77	P
United Kingdom	-0.70	-0.51	-0.41	-0.11	-0.74	-0.80	-0.92	-0.98	-0.46	-0.26	-0.67	-0.75	-0.95	O
United States	1.98	2.28	1.97	1.90	1.49	1.38	1.37	1.43	1.51	1.53	1.44	1.38	1.16	N

Note: Figures in italics are significant at the 10-percent level. The final column indicates whether the trend in the evolution of recursive coefficients is insignificant (O), positive (P), or negative (N) (5-percent significance level).

Figure 5. Public capital ratios for three groups of countries, 1960-2001



Note: The figure shows the differences in the mean (blue bars) and median (red bars) for three groups of countries. In the "P" group public capital has become more productive over time. In the "N" group public capital has become less productive. In the "O" group the productivity of public capital did not change during the 1990s. See the last column of Table 5 for the countries in the various groups.

In Figure 5 we analyse whether there is any difference across the three groups with respect to the

- Average of the public-capital-to-GDP ratio;
- Public-capital-to-private-capital ratio
- Change in the public-capital-to-GDP ratio; and
- Variability in the public-capital-to-GDP ratio.

The blue bar denotes the mean for the group, while the gray bar shows the median.

Productivity of public capital increased in countries where the public capital stock grew.

Figure (5a) suggests that the public capital stock is not systematically different across countries where the impact of public capital on output increased during the 1990s ("P") and those countries where this impact decreased ("N") or remained the same ("O"). The F-statistic of an ANOVA analysis to the test whether the capital stock ratio differs between the three groups is 0.15 ($p = 0.86$).

Figures (5b) and (5d) show that there is also hardly any systematic difference across the three groups of countries with respect to the ratio of public and private capital and the variability of the public capital stock. The F-statistics are 0.14 ($p = 0.87$) and 1.83 ($p = 0.19$), respectively. However, Figure (5c) shows that countries in the “P” group have an increasing capital-stock-to-GDP ratio, while countries in the “N” group saw this ratio decline. Indeed, the test that the change in the capital stock is equal for the three groups can be rejected; the F-statistic is 4.63 ($p = 0.02$).

4.2 Panel VARs

As an alternative to the time-series models reported in Section 3, we also estimate VARs for our panel of countries. We first examine the order of integration of the variables. Recent literature suggests that panel-based unit root tests have higher power than unit root tests based on individual time series. Using Eviews, we have computed five panel unit root tests, namely tests proposed by Levin, Lin and Chu (LLC) (2002), Breitung (BR) (2000), Im, Pesaran and Shin (IPS) (2003), ADF and PP tests (Maddala and Wu 1999 and Choi 2001), and a test suggested by Hadri (2000). While these tests are commonly termed ‘panel unit root’ tests, they are simply multiple-series unit root tests that have been applied to panel data structures. The tests suggested by Levin, Lin and Chu (2002), Breitung (2000), and Hadri (2000) assume that there is a common unit root process that is identical across cross-sections. The first two tests employ a null hypothesis of a unit root, while the Hadri panel unit root test is similar to the KPSS unit root test and has a null hypothesis of no unit root in any of the series in the panel. The Im, Pesaran, and Shin, and the ADF and PP tests allow for individual unit root processes that may vary across cross-sections.

Table 6 shows the outcomes of the panel unit root tests. YES (NO) indicates (no) evidence for a unit root. It becomes clear that the results vary widely across the various tests. While the Hadri test suggests that all series are $I(1)$, the other tests suggest that one or more series may be trend stationary. We proceed under the assumption that all series contain a unit root. This choice can be justified as we also find that the series are cointegrated and that there are two cointegrating vectors (indicated by both the trace test and the maximum eigenvalue test). The number of lags selected is two.

Table 6. Panel unit root tests

	Government capital	Private capital	Output	Hours worked
LLC	NO	NO	NO	YES
BR	NO	NO	NO	YES
IPS	NO	YES	YES	YES
ADF	NO	YES	YES	YES
PP	YES	YES	YES	YES
Hadri	YES	YES	YES	YES

Notes: YES = evidence for unit root; NO = No evidence for unit root. The acronyms in the first column refer to the following tests: Levin, Lin and Chu (LLC), Breitung (BR), Im, Pesaran and Shin (IPS), Augmented Dickey-Fuller (ADF), and Phillips-Perron (PP).

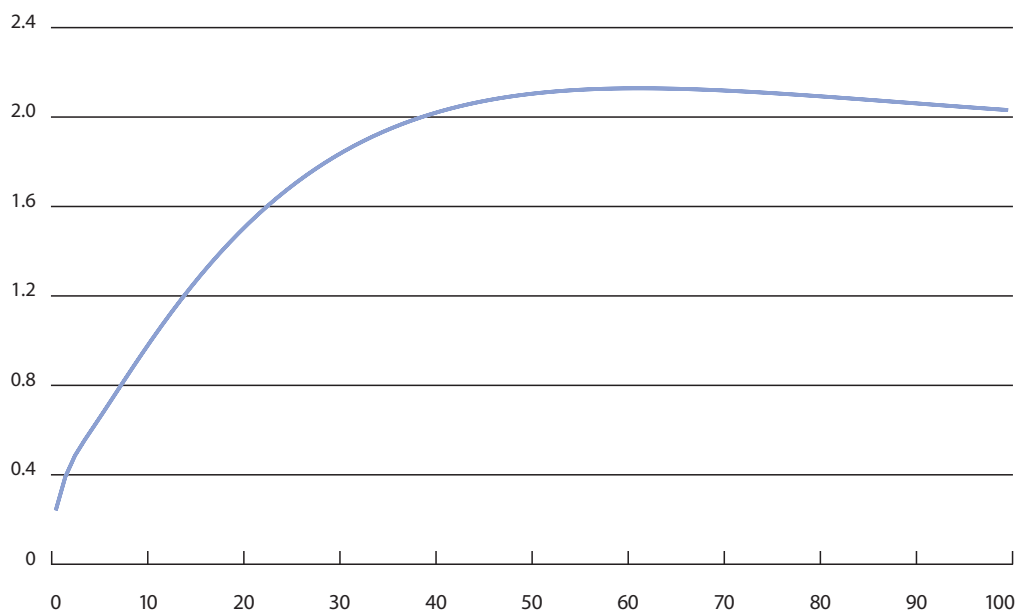
Figure 6 shows the long-run generalized impulse response for output for a one-standard-deviation shock to public capital. The impact of public capital on output is positive but we do not provide confidence intervals. To examine whether the impact of public capital on output has changed over time, we have estimated ‘recursive’ and ‘rolling-window’ VARs. Figure 7 shows the results for the latter; the results for the ‘recursive’ VARs are similar and are therefore not shown. The moving window for the ‘rolling’ VAR is 20 years. So the first VAR that we estimate covers the period 1960-1979

In the panel of countries the impact of public capital on output is positive.

The impact of public capital on output has declined over time.

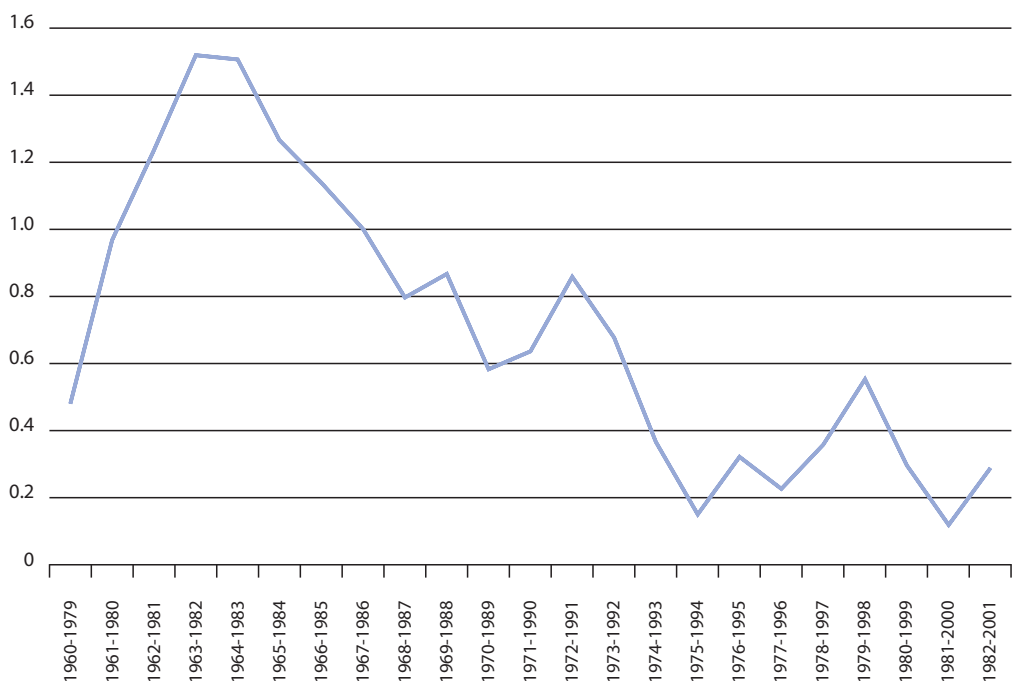
and the last refers to 1982-2001. In line with our findings for the full sample, in all these VARs the number of lags is set to two and two cointegrating vectors are imposed. Figure 7 suggests that the impact of public capital on output has declined over time.

Figure 6. Panel VECM: Impulse response of output to a shock to public capital



Note: The figure shows the impulse response of output to a one-standard-deviation shock to public capital. The horizontal axis shows the number of years after the shock.

Figure 7. Rolling panel VAR: Long-run impact on output of a shock to public capital



Note: The figure shows (for every 20-year rolling window) the estimated long run (semi) elasticity of output with respect to public capital calculated as the response after 20 periods divided by a one standard-deviation shock in public capital.

Overall, the findings of the recursive VARs and rolling-window panel VARs may be interpreted as support for the 'saturation hypothesis', according to which countries with declining marginal productivity of public capital decided to reduce public investment spending. As we have shown in Figure 1, most OECD countries saw their government capital stock in relation to GDP drop during the period under consideration. This may have been a rational decision in view of the declining long-run impact of government capital shown in Figure 7. Indeed, except for Iceland where the public capital stock slightly increased, all countries for which our recursive VARs suggest a decline in the long-run impact on income of a shock to public capital (see Table 5) reduced their public capital stock relative to GDP. However, some caution is needed here as there are alternative explanations for the relative decline in public capital. For example, there is evidence that in times of large fiscal contractions, government capital spending is reduced more than other categories of government spending (see, for instance, De Haan *et al.* 1996).

5. Conclusions

In this paper we have addressed two questions. First, to what extent does the impact of public capital differ across countries? Second, to what extent does it differ over time? In addressing these issues, we have employed Vector Auto Regression (VAR) models as they may best capture the dynamic interactions between variables.

We have applied two approaches. In the first we estimate VAR models for individual countries. We closely follow Kamps (2004) but use a better proxy for labour input (total hours worked), which leads to different results. The estimated long-run impact of public capital on output varies across countries and is negatively correlated with both the ratio of public capital to private capital and the variability of public capital over time. Using recursive VARs, we find that in the majority of countries the effect of a public-capital shock on output decreased during the 1990s. Countries where the impact of public capital on output increased had an increasing capital-to-GDP ratio and *vice versa*.

The second approach, a panel VAR model, has been motivated by the relatively short time span covered by the data for individual countries. Applying a 'rolling' time window, the results confirm that the long-run impact of public capital on output has clearly declined over time.

References

- Aschauer, D.A. (1989). "Is public expenditure productive?". *Journal of Monetary Economics*, (23:2), pp. 177-200.
- Belloc, M. and Vertova, P. (2006). "Public investment and economic performance in highly indebted poor countries: An empirical assessment". *International Review of Applied Economics*, (20:2), pp. 151-170.
- Breitung, J. (2000). "The local power of some unit root tests for panel data", in Baltagi, B. (ed.), *Nonstationary Panels, Panel Cointegration, and Dynamic Panels*, JAI Press, Amsterdam, The Netherlands, pp. 161-178.
- Choi, I. (2001). "Unit root tests for panel data". *Journal of International Money and Finance*, (20:2), pp. 249-272.
- Creel, J. and Pilon, G. (2006). "Is public capital productive in Europe?". OCFE Working Paper No. 2006-10.
- De Haan, J., Sturm, J.E., and Sikken, B.J. (1996). "Government capital formation: Explaining the decline". *Review of World Economics*, (132:1), pp. 55-74.
- Estache, A. and Fay, M. (2007). "Current debates on infrastructure policy". World Bank Policy Research Working Paper No. 4410.
- Gonzalo, J. and Lee, T. (1998). "Pitfalls in testing for long run relationships". *Journal of Econometrics*, (86:1), pp. 129-154.
- Hadri, K. (2000). "Testing for stationarity in heterogeneous panel data". *Econometric Journal*, (3:2), pp. 148-161.
- Hall, P. (1988). "On symmetric bootstrap confidence intervals". *Journal of the Royal Statistical Society*, (B 50:1), pp. 35-45.
- Im, K.S., Pesaran, M.H. and Shin, Y. (2003). "Testing for unit roots in heterogeneous panels". *Journal of Econometrics*, (115:1), pp. 53-74.
- Johansen, S. (1988). "Statistical analysis of cointegration vectors". *Journal of Economic Dynamics and Control*, (12:2-3), pp. 231-254.
- Johansen, S. (1991). "Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models". *Econometrica*, (59:6), pp. 1551-1580.
- Johansen, S. and Juselius, K. (1990). "Maximum Likelihood estimation and inference on cointegration – with applications to the demand for money". *Oxford Bulletin of Economics and Statistics*, (52:2), pp. 169-210.
- Kamps, C. (2004). "The dynamic effects of public capital: VAR evidence for 22 OECD countries". Kiel Working Paper No. 1224, Institute for the World Economy.
- Kamps, C. (2006). "New estimates of government net capital stocks for 22 OECD countries 1960–2001". *IMF Staff Papers*, (53:1), pp. 120-150.

- Kremers, J.J.M., Ericsson, N.R. and Dolado, J.J. (1992). "The power of cointegration tests". *Oxford Bulletin of Economics and Statistics*, (54:3), pp. 325-348.
- Kwiatkowski, D., Phillips, P.C.B., Schmidt, P. and Shin, Y. (1992). "Testing the null hypothesis of stationary against the alternative of a unit root". *Journal of Econometrics*, (54:1-3), pp. 159-178.
- Levin, A., Lin, C.F. and Chu, C. (2002). "Unit root tests in panel data: Asymptotic and finite-sample properties". *Journal of Econometrics*, (108:1), pp. 1-24.
- Ligthart, J.E. (2002). "Public capital and output growth in Portugal: An empirical analysis". *European Review of Economics and Finance*, (1:2), pp. 3-30.
- Maddala, G. S. 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:s1), pp. 631-652.
- Mittnik, S. and Neumann, T. (2001). "Dynamic effects of public investment: Vector autoregressive evidence from six industrialized countries". *Empirical Economics*, (26:2), pp. 429-446.
- Pereira, A.M. (2000). "Is all public capital created equal?". *Review of Economics and Statistics*, (82:3), pp. 513-518.
- Pereira, A.M. (2001). "On the effects of public investment on private investment: what crowds in what?". *Public Finance Review*, (29:1), pp. 3-25.
- Pereira, A.M. and Andraz, J.M. (2005). "Public investment in transportation infrastructure and economic performance in Portugal". *Review of Development Economics*, (9:2), pp. 177-196.
- Pereira, A.M. and Roca-Sagales, O. (2001). "Infrastructure and private sector performance in Spain". *Journal of Policy Modeling*, (23:4), pp. 371-384.
- Pereira, A.M. and Roca-Sagales, O. (2003). "Spillover effects of public capital formation: Evidence from the Spanish regions". *Journal of Urban Economics*, (53), pp. 238-256.
- Pesaran, M.H. and Y. Shin (1998). "Impulse response analysis in linear multivariate models". *Economics Letters*, (58:1), pp. 17-29.
- Phillips, P. (1998). "Impulse response and forecast error variance asymptotics in nonstationary VARs". *Journal of Econometrics*, (83:1-2), pp. 21-56.
- Pina, A.M. and St. Aubyn, M. (2005). "Comparing macroeconomic returns on human and public capital: An empirical analysis of the Portuguese case (1960-2001)". *Journal of Policy Modeling*, (27:5), pp. 585-598.
- Romp, W. and De Haan, J. (2005). "Public capital and economic growth: A critical survey". *EIB Papers*, (10:1), pp. 40-70.
- Schwarz, G. (1978). "Estimating the dimension of a model". *Annals of Statistics*, (6:2), pp. 461-464.
- Sims, C., Stock, J. and Watson, M. (1990). "Inference in linear time series models with some unit roots". *Econometrica*, (58:1), pp. 113-144.
- Voss, G.M. (2002). "Public and private investment in the United States and Canada". *Economic Modelling*, (19:4), pp. 641-664.