Population Aging and Inventive Activity

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October 21, 2019

Abstract

This research empirically establishes and theoretically motivates the hypothesis that population aging has a hump-shaped effect on inventive activity. We estimate this *reduced form, hump-shaped* relationship in a panel of 33 OECD countries over the period 1960-2012, as well as in a panel of 248 NUTS 2 regions in Europe over the period 2001-2012. The increasing part of the hump captures the awareness that population aging requires inventive activity to guarantee current and future standards of living. The decreasing part reflects the tendency of aging societies to lose dynamism and the willingness to take risks. Policy-wise our analysis suggests that raising the acknowledgement of individuals about the consequences of population aging may facilitate the adoption of strategies and policies encouraging inventive activity and economic growth.

Keywords: Population Aging, Inventive Activity, Panel Estimation

JEL Classification Numbers: J11, O31, O50, O57

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1 Introduction

What is the relationship between population aging and the propensity to engage in inventive activity? The answer to this question matters for at least two reasons. The first is related to economic growth. It is widely recognized that population aging poses serious challenges for many important fields of economic policy including health care, pensions or public debt (see, e. g., Rechel *et al.* (2009) or Börsch-Supan (2012)). Economic growth is often seen as a means to solve, or at least to alleviate these problems. Since innovation and technical change are the main drivers of economic growth it is important to know how inventive activities adjust in aging societies. The second reason is cultural. It concerns the hypothesis that old societies tend to lose dynamism, are less forward-looking and more reluctant to accept change. The French demographer, anthropologist and historian Alfred Sauvy *(*Sauvy (1948)*,* p.188*)* put this succinctly:

> *"In countries suffering from ageing, the spirit of enterprise, and hence the willingness to take risks without which capitalism cannot function, gradually atrophies and is replaced by a new feeling: The desire for security."*

If Sauvy's conjecture is true then population aging may lead societies into a state of stagnation with little inventive activity. Yet, is this dismal prediction borne out in the data?

The present paper argues that the relationship between population aging and inventive activity is indeed more intricate. For a panel comprising 33 OECD countries over the period 1960-2012 we empirically establish that the effect of population aging on inventive activity is hump-shaped. Our proxy for population aging is a country's old-age dependency ratio, OADR.[1] We use the number of patent applications per 1000 residents to measure a country's propensity to engage in inventive activity. For the whole panel the estimated peak of the hump occurs at an OADR between 24 and 27, roughly the OADR of Japan for the period 1999-2003 and of Germany for the period 2001-2004. In countries to the left of this critical level the propensity to engage in inventive activity increases, ceteris paribus, with population aging. The opposite holds for countries to the right. We also obtain qualitatively similar results for a panel of 248 European NUTS 2 regions over the period 2001-2012.

Where does the hump come from? Our interpretation of this empirical finding assumes two simultaneous relationships between inventive activity and population aging (see Figure 1 for an illustration).[2] The first is increasing and dominates the overall relationship to the left

[1] The OADR is the ratio of the economically dependent old (people older than 64) to the working population aged 15-64. Throughout, this ratio is stated as the number of dependent old per 100 members of the working-age population. The source of our data is the World Bank Indicators.

[2] Here Ω and P denote the OADR and patents per 100,000 inhabitants, respectively. The first, increasing relationship is $P = f(\Omega)$ where $f : \mathbb{R}_{++} \rightarrow \mathbb{R}_{++}$ with $f'(\Omega) > 0 > f''(\Omega)$. The second, decreasing relationship is $P = g(\Omega)$ where $g : \mathbb{R}_{++} \rightarrow \mathbb{R}_{++}$ with $g'(\Omega) < 0$ and $g''(\Omega) < 0$. Then, the sum of these two relationships

of the hump, the second is decreasing and dominates to its right. The increasing relationship may capture the spirit of the saying "necessity is the mother of invention." Inventive activity is necessary in aging populations to raise the productivity of the working young. This guarantees a decent standard of living for the economically dependent old while keeping the burden of the supporting working young at an acceptable level. Therefore, we would expect that aging societies implement institutions and policies that foster inventive activity. The decreasing relationship captures the spirit of Sauvy's conjecture as well as a tendency of aging societies to direct resources to pensions de Mello *et al.* (2017).

The main result of our empirical part suggests that the sum of these two relationships is strictly concave and hump-shaped with a unique interior maximum. Hence, our empirical strategy identifies the reduced form, *i.e., the aggregate effect,* of two broadly defined and opposing trends.

The explicit identification of all potential mechanisms and their effects on the two opposing trends is beyond the scope of this paper. However in the discussion section we explore some mechanisms, e.g., the life-cycle hypothesis and the role of pension schemes (see Table 11). We find that our aggregate result survives these robustness checks. Further inquiry into the determinants of these two opposing trends is a fruitful research agenda. For instance, our companion paper, Irmen and Litina (2017a), has a detailed empirical analysis of one of the multiple channels, the cultural channel. There, we establish that population aging also has a hump-shaped effect on individual attitudes towards new ideas and innovation.

What could policy makers learn from our empirical findings? Clearly, some received policy responses such as encouraging immigration, raising workers' education, or shifting the retirement age are not related to the scope of our inquiry. However, our analysis suggests that a policy of raising the individual awareness about the consequences of population aging is called for. Indeed, informing individuals about the costs and benefits of population aging is likely to change their attitudes towards inventive activity. As a consequence, both relationships shown in Figure 1 should move upwards. Hence, for all levels of population aging the propensity to engage in inventive activity will increase. Under mild conditions this will even lead to a rightward shift of the hump. This is shown in Figure 2.[3] Thus, raising awareness may place aging countries from the right to the left of the hump. This is the case for all countries

is $h(\Omega) = f(\Omega) + g(\Omega)$ where $h : \mathbb{R}_{++} \to \mathbb{R}_{++}$ and $h''(\Omega) < 0$. The critical OADR, Ω^*, satisfies $h'(\Omega^*) = f'(\Omega^*) + g'(\Omega^*) = 0$. If f and g are such that $\lim_{\Omega \to 0} h'(\Omega) > 0$ and $\lim_{\Omega \to \infty} h'(\Omega) < 0$ then a unique $\Omega^* \in (0, \infty)$ exists which gives a global maximum of h.

[3] Figure 2 extends the setup of Figure 1 explained in Footnote 2. Now, we write the first and the second relationships respectively as $P = f(\Omega, x)$ where $f : \mathbb{R}^2_{++} \to \mathbb{R}_{++}$ and $P = g(\Omega, x)$ where $g : \mathbb{R}^2_{++} \to \mathbb{R}_{++}$. Here, $x > 0$ reflects the degree of awareness that shifts both relationships upwards, i. e., the partial derivatives with respect to x are $f_x(\Omega, x) > 0$ and $g_x(\Omega, x) > 0$. In Figure 2 both relationships shift upwards as $x' > x$. Moreover, we maintain that $f_\Omega(\Omega, x) > 0 > f_{\Omega\Omega}(\Omega, x)$, $g_\Omega(\Omega, x) < 0$, and $g_{\Omega\Omega}(\Omega, x) < 0$. Then, $h(\Omega, x) = f(\Omega, x) + g(\Omega, x)$ where $h : \mathbb{R}^2_{++} \to \mathbb{R}_{++}$, $h_{\Omega\Omega}(\Omega, x) < 0$ and $h_x(\Omega, x) > 0$. The critical OADR satisfies $h_\Omega(\Omega^*, x) = f_\Omega(\Omega^*, x) + g_\Omega(\Omega^*, x) = 0$.

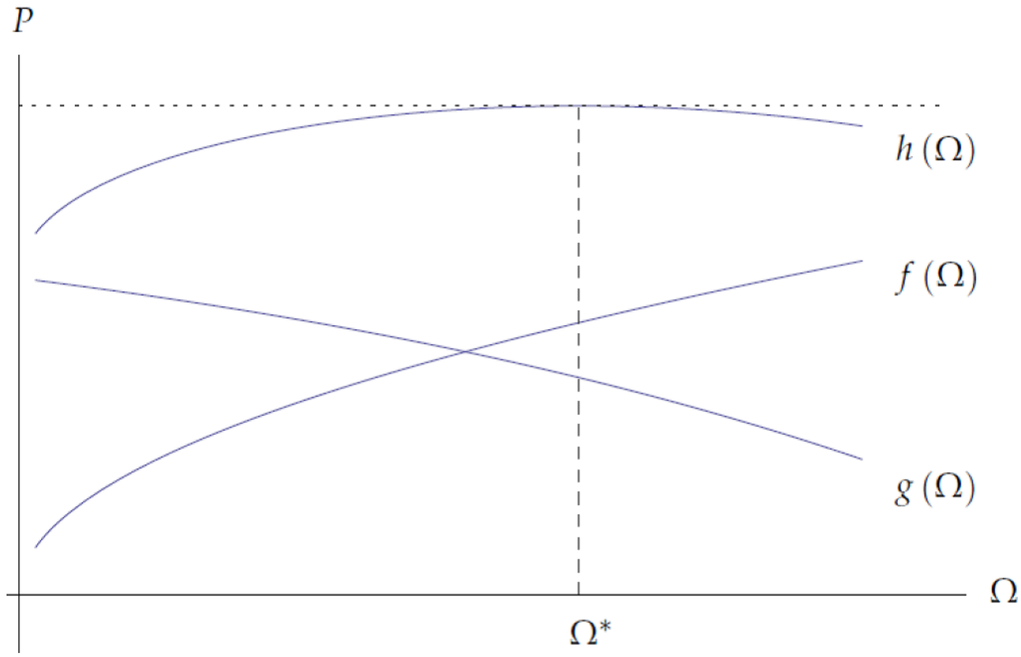

FIGURE 1: Inventive activity as a concave, hump-shaped function of population aging. Here, Ω denotes the OADR, whereas P represents patents per capita.

with an initial OADR, $\Omega \in [\Omega^*,\ (\Omega^*)']$. Hence, such a policy may facilitate the adoption of strategies encouraging inventive activity and thus economic growth in an attempt to alleviate the adverse consequences of population aging.

We derive our empirical results estimating a panel with country and time fixed effects to capture a large number of time and country-specific unobservables. Moreover, we include a wide range of aggregate level controls including per-capita income, life expectancy, fertility and mortality, institutions, urbanization, aggregate national expenditure (including public spending on education and health), and trade flows. To establish a causal effect of population aging on inventive activity we conduct an IV estimation as well a number of robustness checks testing the different assumptions of our model and accounting for potential confounders of inventive activity.

Arguably, our panel analysis may neglect important controls since appropriate data, e.g., on R&D and health spending, or on the number of researchers in R&D are not available for the full set of countries and years. To address this issue, we study in addition a more demanding specification, using richer data of 248 European NUTS 2 regions that belonged to

Now, assume that more awareness - a greater x - also increases the slopes f_Ω and g_Ω so that $f_{\Omega x}(\Omega, x) > 0$ and $g_{\Omega x}(\Omega, x) > 0$. Then, the implicit function theorem delivers

$$\frac{d\Omega^*}{dx} = -\frac{f_{\Omega x}(\Omega^*, x) + g_{\Omega x}(\Omega^*, x)}{h_{\Omega\Omega}(\Omega^*, x)} > 0.$$

Hence, for a greater level of awareness the global maximum of h occurs at a greater OADR.

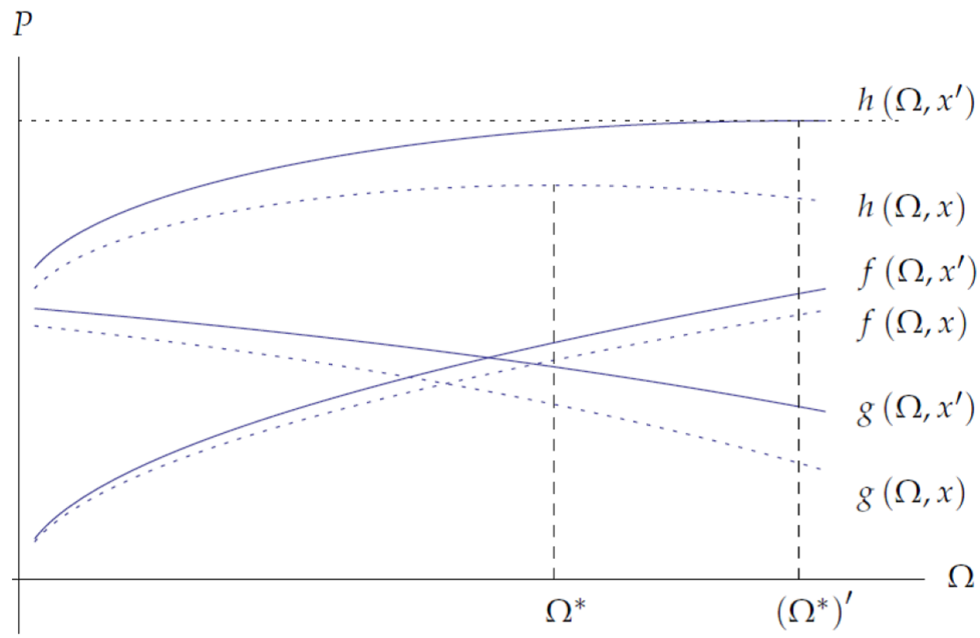

FIGURE 2: A policy of raising awareness about the costs and benefits of population aging may shift the hump to the right.

the OECD for the period 2001-2012. This analysis allows us to introduce regional fixed effects that eliminate unobserved heterogeneity at a highly disaggregated regional level. These fixed effects net out relevant country-wide controls like government spending

Our paper is closely related to the recent empirical and theoretical literature on the consequences of demographic change and population aging for economic performance (see, Weil (1997) or Bloom and Sousa-Poza (2013) for selective surveys). For instance, Kogel (2005) argues that a higher youth dependency ratio reduces 'residual', i. e., total factor productivity growth. The focus of Feyrer (2007) is on the relationship between workforce demographics and aggregate productivity. According to this author changes in the age structure of the workforce are significantly correlated with changes in aggregate productivity. Kulish *et al.* (2010) show that the aging increases capital intensity in the long-run, but decreases it in the short-run. Poterba (2014) explores the effect of population aging on a wider range of issues including life-cycle planning and retirement. He also argues that an aging population may be associated with a declining rate of innovation. Cai and Stoyanov (2016) establish that population aging leads to specialization in industries which use age-appreciating skills intensively and erodes comparative advantage in industries for which age-depreciating skills are more important.

Marconi (2018) finds that in a panel of 118 countries, changes in the level of education of population aged 45-64 is associated with increases in income per capita. The study of Maestas *et al.* (2016) seems to confirm Robert Gordon's view of aging as a headwind for U.S. economic growth (Gordon (2016), p. 627). These authors study population aging across U.S.

states over the period 1980-2010. They find that a 10% increase in fraction of the population older than 60 decreases the growth rate of GDP per capita by 5.5%. The evidence provided by Acemoglu and Restrepo (2017) for a broad set of 169 countries over the period 1990-2015 suggests that aging societies have seen their per-capita GDP grow faster.

Recent theoretical contributions underline that the two tendencies emphasized in the present paper have sound economic underpinnings. For instance, Heer and Irmen (2014) and Irmen (2017) argue that aging populations will invest more to raise the productivity of the workforce. This leads to faster per-capita GDP growth unless the role of capital-augmenting technical change becomes relevant. ize the beneficial role of aging-induced increases in the stock of physical and human capital. Our empirical analysis controls for these channels and enrich this literature by accounting for the downward sloping part of the hump.

The literature on the consequences of population aging for economic growth in dynamic economies with probabilistic voting suggests a negative relationship between population aging and economic growth (see, e.g., Kuehnel (2011) or Gonzalez-Eiras and Niepelt (2012)). Here, population aging implies that the median voter gets older. Then, the political-economic equilibrium shifts in favor of the old implying less inventive activity and slower economic growth. However, these models feature no counterpart to the necessity-is-the-mother-of-invention motive.

To the best of our knowledge the present paper is the first that explores the direct link between population aging and inventive activity at the macroeconomic level across countries and time as well as across regions and over time. Moreover, unlike the above-mentioned literature that predicts linear effects we uncover a non-linear, hump-shaped effect of population aging on inventive activity. In other words, the direction of the effect of population aging hinges on its level.

The structure of the present paper is the following. Section 2 describes the empirical strategy and the data used in our paper. Section 3 presents the empirical results for our main research question. Section 4 conducts robustness tests. This section also includes the regional analysis which captures a larger number of unobservables. Section 5 discusses several issues of interest related to our findings whereas Section 6 concludes. The definitions and the sources of the variables used in our analysis are provided in an Appendix.

2 Data and Empirical Strategy: Panel Data Analysis of 33 OECD Countries

This section serves two purposes. First, we describe our data in Section 2.1. Second, we explain our empirical strategy in Section 2.2.

2.1 The Data

We study the effect of population aging on inventive activity in an unbalanced panel data set of 33 OECD countries including Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, South Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States. For these countries the full set of controls used in the baseline model is available. This is not the case for Iceland which is therefore excluded. We consider annual data for the period 1963-2010.[4] We consider the included OECD countries as a representative set of the world's industrialized countries that already face the threat of an aging population.[5]

Our proxy for inventive activity is the number of patent applications filed per 1000 inhabitants. The data is available from the World Development Indicators (WDI), and the original source is the World Intellectual Property Organization (WIPO). WIPO is a very systematic source of filing patents applications all over the worlds in a way that makes comparisons across countries feasible. We choose patent applications as opposed to actual patents to avoid concerns associated with the system of patent granting. As such, patent applications appear to be a better proxy for the inventive activity of a given year. In Section 4, we use the number of researchers in the Research and Development sector per million people as an alternative proxy for inventive activity. Here, the source is again the World Development Indicators.

Our dependent variable is the old-age dependency ratio (OADR) which we interpret as the proxy for population aging. The OADR states the number of people above the age of 65 -the old- per 100 people of the working population aged 15-64. In Section 4 we use the number of old people per 100 members of the *total population* as a measure of population aging and we show that our main results still hold. Moreover, we conduct *placebo* tests with the young age dependency ratio, i.e., the ratio of young people (below 15) per 100 members of the working age population.

Our analysis controls for a wide range of confounders, also available from the WDI. They include income per capita, life expectancy, fertility and mortality rates, urbanization, institutional quality, gross national expenditure, GNE, and trade flows as a percentage of GDP. All of these variables qualify as plausible determinants of inventive activity. Section 4 takes additional controls into account that are only available for shorter time periods or for fewer

[4] Our panel is unbalanced. However, for country level data this is not due to attrition and, therefore, of little concern. The sample of already developed OECD countries mitigates this concern even further. Moreover, we replicated our analysis taking 3-year and 5-year aggregates of all included variables. This reduces the role of missing observations and absorbs the potential effect of cyclical fluctuations. We show in Section 4 that our main result remains valid with 3-year and 5-year aggregates.

[5] In Section 4 we establish that our results hold for alternative samples as well as for the sample of 123 countries for which the full set of baseline controls is available.

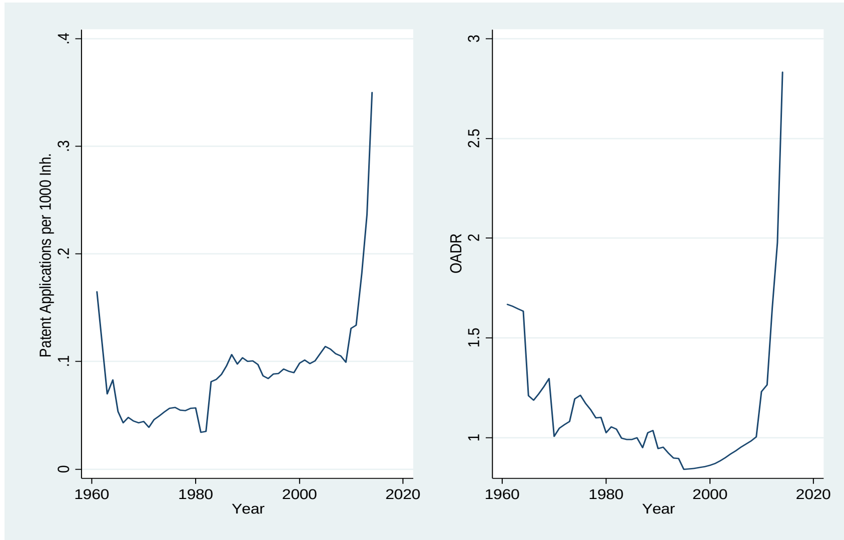

FIGURE 3: Mean Values (for all Years Averaged Across Countries) of OADR and Patent Applications.

countries. They include population density, secondary enrollment rates, the ICRG measure of corruption, unemployment rates, and immigration stocks. We do not employ all these controls in the baseline model to keep the sample as large as possible.

[TABLE 1 ABOUT HERE]

[TABLE 2 ABOUT HERE]

Tables 1 and 2 provide the summary statistics for the sample of 33 countries over the period 1960-2012. The panel has 1225 observations. The sample features primarily developed countries with a mean annual per-capita income of 23,706 in constant $2005. Most of these countries were democratic throughout most of the years with an average institutional quality score of approximately 8.5 on a scale from -10 to 10. The average life expectancy at birth is 75 years, the average total fertility rate is 2 births per woman.

The number of patent applications per 1000 inhabitants also varies considerably from 0.001 (again for Turkey in the 70's) to 3.028 for Japan (during the last decade). We observe that the mean value of inventions increases steadily roughly from 1970 onwards (see left panel of Figure 3). After the year 2005 there is a pronounced increase in the mean number of patent applications in some countries such as Japan, Korea, USA, Denmark or Finland moving faster. Similarly, in this set of countries the OADR varies from 6 (for Turkey in the 70's) to 39 (for Japan during the last decade). The OADR decreases slightly between 1960 and approximately 2005. After this period we see a sharp increase (see the right panel of Figure 3).

2.2 Empirical Strategy

This section introduces our baseline model as well as our IV estimation.

2.2.1 The Baseline Model

We estimate the baseline model described by

$$P_{it} = \alpha_0 + \alpha_1 \Omega_{it} + \alpha_2 \Omega_{it}^2 + \alpha_3 \mathbf{X}_{it} + \alpha_4 \mathbf{I}_i + \alpha_5 \mathbf{T}_t + \varepsilon_{it}. \tag{1}$$

Here, P_{it} is the number of patent applications per 1000 inhabitants filed by residents of country i at time t. The OADR is denoted by Ω_{it}, whereas Ω_{it}^2 is its squared value. The presence of the quadratic term allows for the identification of a non-linear effect of population aging on inventive activity.[6] We use the contemporaneous values of the OADR in the baseline specification. This suggests a contemporaneous effect of population aging on inventive activity. However, as shown in the robustness section our results are robust to the use of lagged values of the OADR, lead values of the OADR to proxy aging projections as well in specifications with 3 and 5-year averages.

The vector of confounders, $\mathbf{X}_{it}$, includes a large number of time varying controls that may have an effect on inventive activity. It includes income per capita, life expectancy, fertility and mortality rates, urbanization rates, institutional quality, gross national expenditure, and international trade flows, both as a percentage of GDP. The vector of country fixed effects, $\mathbf{I}_i$, captures unobserved heterogeneity at the country level, at least for time invariant characteristics such as geography or climate. The vector of year fixed effects, $\mathbf{T}_t$, captures time specific shocks, e.g., the presence of the baby-boom generation across countries. Finally, ε_{it} is the country and time specific error term.

2.2.2 IV Estimation

Reverse causality and omitted variable bias may conflate our estimations even though we control for many sources of unobserved heterogeneity via time-varying controls, country and time fixed effects.[7] To further address potential endogeneity concerns we adopt an IV estimation of our baseline model.[8]

An omitted variable bias may matter if there is some unobserved or omitted variable that simultaneously affects population aging and inventive activity. We use rates of immu-

[6] In Section 4 we investigate the non-linear specification further. In particular, we show that neither a purely linear specification nor an additional cubic term is supported by the data.

[7] In addition, in Section 4 we show that our results also hold in a first-differences model and in a dynamic panel analysis.

[8] In Section 4 we further discuss both sources of endogeneity. Specifically, we use the lagged values of population aging to address reverse causality. Moreover, we replicate the analysis of our baseline model using patent applications in specific sectors as the dependent variable.

nization against measles as an instrument. Measles is an infection of the respiratory system, immune system and skin caused by a virus (Griffin, 2002). It is a particularly contagious disease that affects primarily children but anyone may be contaminated who has not been immunized against the disease. Whereas the fight against the disease is quite advanced, it may nevertheless create complications and lead to death. Crucially, the symptoms of the disease become more severe with age. For 2011, the World Health Organization estimates that approximately 158,000 people died worldwide of measles (as opposed to e.g., 469.978 women being at risk for maternal death for the same year according to the WDI for a sample of 163 countries), whereas in 1990 this number was as high as 630,000. In developed countries 1% of people infected with measles may die from complications whereas in developing countries this rate is as high as 10%.[9] Treatments against measles are available, however, the best protection is immunization.

We use a child immunization measure as an instrument. More precisely, our instrument is the fraction of children aged 12-23 months who received a vaccination before their 12th month. A child is considered adequately immunized against measles after receiving one dose of vaccine. The data is part of the World Development Indicators. A mechanism through which our instrument affects the endogenous regressor, OADR, operates via positive spill-overs of immunization to the health status of the population as a whole. If this status improves then the fraction of the old in the population, who are on average more vulnerable, tends to increase.[10] Whereas vaccination is the best protection against the disease, not all OECD countries impose mandatory vaccination. Our IV strategy exploits this variation in vaccination rates.[11]

Our identifying assumption is that country specific levels of immunization against measles are not correlated with patents filed each year by residents of the respective country. This is quite plausible. Since the 1960's the quality of the vaccine against measles is so advanced that the total population may be protected provided that all individuals are vaccinated. Therefore, it is very unlikely that recent inventive efforts are still targeted towards improving the vaccine against measles. This argument also rules out a causality running from patents to vaccination rates.

Potentially, measles may affect inventive activity via other, indirect channels. We introduce a number of time varying controls to address this issue. In particular, we use life

[9] WHO Factsheet: http://www.who.int/mediacentre/factsheets/fs286/en/ (accessed on March 15, 2016).

[10] One could think of weakening effects. However the unconditional correlation between our instrument and the endogenous regressor is positive ($\simeq 0.18$). Moreover the conditional correlation is also positive and highly significant (see Table 4 below).

[11] Data on recent outbreaks of measles are quite revealing as to the negative externality of low rates of immunization. In 2007, an outbreak of measles in Japan prompted a closing of universities and other public institutions in an attempt to contain the spread of the disease. In 2008, measle epidemics were reported in Austria, Italy, Switzerland and the UK with more than 1200 reported cases in the latter country. Similarly in 2009, two schools in Wales were closed after an outbreak of the disease. France had 17,000 reported cases of measles between 2008 and 2011 with 8 fatalities. In the US, more than 500 people died of measles every year during the last decade.

expectancy and mortality rates to control for the potential effect that immunization against measles could have on the health capital of individuals which, in turn, could improve their capacity to innovate. Moreover, we control for gross national expenditure which includes spending on education and health. Whereas the former captures a potential effect of vaccination on the incentives to build human capital, the latter captures changes in the allocation of funds to health issues. It is hard to argue that immunization against measles could be systematically correlated with any of the above factors. Nevertheless, controlling for them further supports the claim that our IV strategy satisfies the exclusion restriction.

Hence, the fraction of children immunized against measles is a valid instrument for the OADR. Since the second stage is quadratic in the endogenous regressor, it is necessary for the 2SLS regression to instrument for both the OADR and its squared term. Then, the system of equations is exactly identified. We apply the two step procedure suggested by Wooldridge (2010), Section 9.5. First, the OADR is regressed on the fraction of children immunized against measles using all second-stage controls. This delivers predicted values of the OADR. The predicted OADR from the first stage is then squared. Finally, this value is used as an excluded instrument in the second stage along with the instrument "rates of immunization against measles."

3 Empirical Findings

This section develops our findings for the baseline model and for the IV estimation.

3.1 Findings for the Baseline Model

Column (1) of Table 3 shows that the estimated value of α_1 is strictly positive whereas the estimated value of α_2 is strictly negative. Both estimates are significant at the 1% level. This specification has year and country fixed effects. Hence, the effect of population aging on inventive activity is hump-shaped. The hump attains a maximum of 4.18 patents per 1000 inhabitants at an OADR of approximately 24.42.

[TABLE 3 ABOUT HERE]

The remaining columns gradually introduce our additional time varying controls that are available for the baseline model.[12] Column (2) introduces a control for income per capita to capture the stage of development of the country. As anticipated, higher levels of income are associated with a higher number of patent applications. Column (3) adds three demographic

[12]Section 4 uses a smaller sample in order to control for an even larger number of time varying controls. As Table 8 illustrates, the results are unaffected by the addition of these controls. The coefficients as well as R-squared remain roughly stable, implying that unobservables do not appear to be of concern.

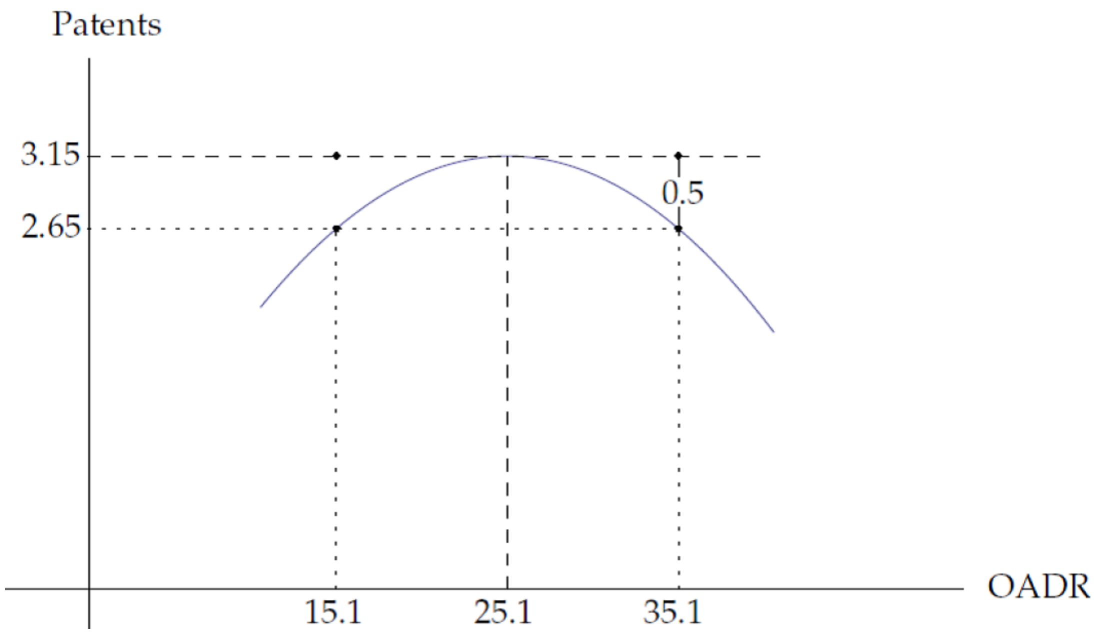

FIGURE 4: Properties of the hump for the baseline model.

controls, mortality rates, life expectancy and fertility rates, that may capture a long lasting effect on the incentives of individuals to invest in education and on their ability to invent. Only life expectancy confers a statistically significant effect which comes with a negative coefficient, perhaps reflecting the fact that all countries in the sample are in the post-demographic transition period. Column (4) augments the set of controls with the urbanization rate to capture the effects of clustering around cities and of increasing returns due to agglomeration. Columns (5) and (6) present the results obtained with the inclusion of institutional quality and of gross national expenditure. GNE, i.e., gross national expenditure as a percentage of GDP, includes all types of government final consumption. Hence, this variable implicitly controls for public level investments in health and education infrastructure.[13] Interestingly, all these controls are insignificant, perhaps because the suggested channels are already captured by the control "Log Income per Capita."

Finally, Column (7) adds the control "Trade Flows as a % of GDP." The coefficient is negative and significant implying that the higher the trade volume the lower is the number of patent applications. This result could be related to trade crowding out domestic inventive activity. Henceforth, we shall refer to the specification in Column (7), which includes the full set of controls, as the baseline specification.

Reassuringly, the regressions of Columns (1) to (7) suggest a significant effect of population aging on inventive activity. Moreover, the estimated coefficients for $OADR$ and

[13] We use the aggregate measure GNE since this is the only measure available for such a long period. A disaggregation of GNE is possible but data is only available for shorter time periods.

for $OADR^2$ remain remarkably stable in all columns. Turning to some orders of magnitude, notice that the hump attains its maximum of 3.15 patents per 1000 inhabitants at an OADR of approximately 25.1. This is illustrated in Figure 4. For countries like Japan or Germany with an OADR in 2010 of about 36 and 32, respectively, further population aging is predicted to have an adverse effect on inventive activity, holding everything else constant. On the contrary, countries like Israel with an OADR of 17 or Canada with an OADR of 20 in 2010 find themselves to the left of the hump's maximum. Therefore, further population aging is predicted to increase inventive activity. At its peak a 10 point change in the OADR (i.e., moving the OADR to 35.1 or to 15.1) is associated with a decrease in the number of patent applications per 1000 inhabitants of 0.5. Roughly, this corresponds to a decline of 16%. Given that the range of "patents per 1000 inhabitants" in our sample extends from 0 to 3 the order of magnitude of this decline is substantial.

3.2 Findings for the IV Estimation

The findings of our baseline specification suggest that the results are not merely reflecting the possible influence of some unobserved country-specific attributes. The finding that population aging has a significant hump-shaped correlation with inventive activity appears to be quite robust and the coefficients are quite stable across specifications. However, to further mitigate potential endogeneity concerns, this section presents the IV estimation outlined above.

Endogeneity is either due to reverse causality or to unobservables. The reverse causality issue is addressed in Section 4, where lagged values of the old-age dependency ratio replace contemporaneous values. Our IV strategy addresses both types of endogeneity. As described in the previous section, our instrumental variables are the fraction of children aged 1-3 immunized against measles and the predicted value of the OADR.

[TABLE 4 ABOUT HERE]

The results of our IV estimation are shown in Table 4. We use the same sample of 33 OECD countries as above. Due to limited data on measle immunization rates for earlier periods we restrict attention to the time period 1980-2012.

Column (1) reports the OLS results obtained for the full set of controls used in our baseline specification. Comparing this to Column (7) of Table 3 reveals that the coefficients are somewhat larger for the IV estimation.

Columns (2) and (3) present the results of the first stage regression (reported in the upper part of the table). It suggests that immunization against measles has a positive and statistically significant effect on the old-age dependency ratio for both the linear and the quadratic terms.

Column (4) presents the results of the second stage of the 2SLS procedure. The dependent variable, i.e., the number of patents per 1000 inhabitants, is now regressed on the linear and the quadratic term of the old-age dependency ratio, instrumented by the measles immunization rate and the predicted quadratic term of the OADR. Moreover, the full set of controls of our baseline model is used. Reassuringly, the effect of both the linear and the quadratic coefficients of population aging on patents remains hump-shaped and statistically significant at the 1% level. Moreover, the weak identification test suggests that we must reject the null hypothesis of weak identification.

The coefficients remain quite stable, potentially reflecting the fact that endogeneity and omitted variables bias is not a major concern in the context of our analysis. Interestingly, the maximum of the hump under the IV estimation is at a level of 3.1 patents per 1000 inhabitants. This is roughly the same value obtained for our baseline regression. However, under the IV estimation this maximum is attained at an OADR of roughly 29 whereas in the baseline regression the corresponding OADR is roughly 25. The reason is that for the time period considered in the IV estimation the mean OADR has increased. Thus, compared to Table 3 population aging is conducive to inventive activity at even higher levels of the OADR.

4 Robustness

In this section we conduct a series of robustness checks to test the validity of our analysis to a number of different assumptions and specifications. Moreover, we conduct a regional analysis, in a sample of NUTS 2 regions in Europe in order to capture a large number of unobservables not only at the country but also at the regional level.

4.1 External Validity

One important question is whether our main result holds only for the sample of OECD countries or whether it is also valid for a wider range of countries. As discussed in Section 2.1, we consider the 33 OECD countries as a natural set of countries where population aging is a plausible concern. Here, we show that our main result is also valid for the complete set of the worlds' countries for which data is available. Moreover it is valid for the subset of countries selected under different assumptions.

[TABLE 5 ABOUT HERE]

Consider Table 5. Column (1) uses a world sample whereas Column (2) is based on a sample of non-OECD countries. Columns (3) - (5) use samples of countries where life expectancy is higher than 50 years, higher than 60 years, or higher than 70 years, respectively.

Columns (6) - (8) is based on samples of countries where, respectively, the birth rate is lower than 4, 3, or 2 children per women. The regressions in all columns feature the full set of controls used in the baseline specification.

Our findings may be interpreted as follows. First, our main result is confirmed in all samples except for the non-OECD countries. This suggests that the result is primarily driven by countries faced with the threat of an aging population. Moreover, our results become increasingly stronger once we move to countries were population aging is an imminent problem since life expectancy is higher and/or fertility is lower. As far as the peak of the hump is concerned the effect of population aging on inventive activity reverses at higher levels of the OADR as we move to older countries. For instance for the whole world the peak occurs at a level of 26.5, whereas for countries with life expectancy higher than 70 years the peak occurs at 30.

4.2 Alternative Specifications

Table 6 shows the results for several alternative specifications. The full set of controls available for the baseline model is always employed.

[TABLE 6 ABOUT HERE]

Column (1) uses lagged values of the OADR as the main explanatory variable of inventive activity. Our estimates are similar in magnitude and significance to the baseline regression. This finding further mitigates potential concerns about reverse causality.

Column (2) tests whether five year leads in the OADR variable have an effect on inventive activity. The idea is to scrutinize the hypothesis of (DellaVigna and Pollet, 2007), who argue that demographic change is easy to predict and thus we would expect it to affect inventive activity "early on". While systematic data on current projections for future aging are available for recent years, the same is not true for projections on aging back in 1960's. Thus, we make the implicit assumption that future values of aging are close to the predicted ones, and we use 5-year leads to proxy aging projections. The results remain qualitatively and quantitatively similar. What changes though is the peak of the hump, which increases compared to the other columns.

Column (3) shows the findings of a first-difference model. Our main result remains largely intact with both coefficients reducing somewhat in magnitude.

Column (4) adopts a more demanding specification and estimates a dynamic panel model. We interpret our findings with caution as the dynamic panel format introduces a bias into our model.[14] Our findings are still significant at the 5% and 10% level, whereas the

[14] Whereas the coexistence of country fixed effects and of lagged values of the dependent variable may yield inconsistent estimates, the bias nevertheless gets smaller in magnitude and ultimately becomes negligible as

coefficient of lagged patents is highly significant. Hence, introducing some inertia coming from R&D of the previous period somewhat tends to lower the OADR at which the hump peaks. It is now at a level of 22.6.

Column (5) adds time trends to capture omitted trends that affect all OECD countries. This also leaves our main result unchanged.

Finally, Columns (6) and (7) shows the results using, respectively, 3-year and 5-year aggregates of all included variables. Our main result is robust to both aggregations. This reduces the role of missing observations and absorbs the potential effect of cyclical fluctuations.

[TABLE 7 ABOUT HERE]

The specifications of Table 7 further challenge our choice of a quadratic estimation. Column (1) in Table 7 explores the alternative of a linear specification. Clearly, the linear relationship is not supported by the data. Column (2) introduces a cubic specification. All three terms are highly significant. However, the coefficient on the cubic term is equal to 0, thus supporting our choice of a quadratic specification.

4.3 Additional Controls

Our baseline specification includes a set of controls that maximizes the number of observations. Additional controls that are only available for a shorter time period or for fewer countries are introduced in Table 8. They include population density, secondary enrollment rates, the ICRG measure of corruption, unemployment rates, and immigration stocks. Moreover, we include explicit controls for tertiary education to capture the fraction of people with a university degree who most likely engage in inventive activity (Toivanen and Väänänen, 2016). All these controls could confer an effect on inventive activity. Introducing these controls gradually on top of the controls used for the baseline specification does not alter our main result. The peak of the hump remains roughly at a level of the OADR equal to 25. Hence, the inclusion of a wide range of time varying controls along with the fixed effect estimator indicates that unobservables are not driving the results.

The issue of additional controls is further addressed in the regional analysis, where the addition of regional fixed effects allows to account for an even larger number of unobservables not only at the country but also at the regional level.

[TABLE 8 ABOUT HERE]

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the time dimension reaches infinity (Nickell, 1981). Judson and Owen (1999) suggest that the bias on the lagged dependent variable is around 2-3% for 20 periods. This number drops to 1-2% for 30 periods.

4.4 Cross-Sectional Dependence and Unit Roots

We conducted Fisher type unit root tests (Choi, 2001) as well as the Peasaran test for cross-sectional dependence (Pesaran, 2004). Our findings (not reported but available upon request) do not suggest cross-sectional dependence or the presence of a unit root.

4.5 Outliers

In order to account for potential outliers, we conduct a weighted regression test where the most influential points are dropped, and sequentially cases with large absolute residuals are down-weighted. The results (not reported but available upon request) remain qualitatively unaffected.

4.6 Panel Data Analysis of Nuts 2 Regions

In this section we replicate the baseline analysis of the effect of population aging on inventive activity in a panel of Nuts 2 regions in Europe. This allows us to capture a larger number of unobservables which helps to eliminate most of the unobserved heterogeneity present at the regional and the country level.

4.6.1 Data and Empirical Strategy

Our sample consists of 248 Nuts 2 regions that belong to 21 European countries, i.e., Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. The period for which the regional data is available is 2001-2012 (annual data). As in the baseline analysis we include only OECD countries.

As in the baseline analysis, our proxy for inventive activity is the number of patent applications filed per 1000 inhabitants. Our dependent variable is the old-age dependency ratio (OADR), i.e., the number of people above the age of 65 -the old- per working-age population aged 15-64. The data is available from Eurostat.

We estimate the following model:

$$P_{rt} = \alpha_0 + \alpha_1 \Omega_{rt} + \alpha_2 \Omega_{rt}^2 + \alpha_3 \mathbf{W}_{rt} + \alpha_4 \mathbf{R}_r + \alpha_5 \mathbf{T}_r + \varepsilon_{rt}. \tag{2}$$

Here, P_{rt} is the number of patent applications per 1000 inhabitants filed by residents of region r at time t. The OADR is denoted by Ω_{rt}, whereas Ω_{rt}^2 is its squared value. The vector of confounders, $\mathbf{W}_{rt}$, includes a set of time varying controls that may have an effect on inventive activity such as income per capita, life expectancy, fertility and mortality rates, and individuals with tertiary education. The vector of regional fixed effects, $\mathbf{R}_r$, captures unobserved heterogeneity at the regional level (NUTS 2), at least for time invariant characteristics such as geography or climate. Thus, compared to the baseline model, we capture unobserved heterogeneity not only at the country level, but more importantly at the regional level. The vector of year fixed effects, $\mathbf{T}_t$, captures time specific shocks. Finally, ε_{rt} is the region and time specific error term.

4.6.2 Findings for the Panel Data Analysis of Nuts 2 Regions

Column (1) of Table 9 shows that the estimated value of α_1 is strictly positive whereas the estimated value of α_2 is strictly negative. Both estimates are significant at the 1% level. Hence, the effect of population aging on inventive activity is hump-shaped. The hump attains a maximum at an OADR of approximately 26.5.

[TABLE 9 ABOUT HERE]

The remaining columns gradually introduce our additional controls. Column (2) adds year and regional (NUTS 2) fixed effects. This eliminates any unobserved heterogeneity at the NUTS 2 level (that remains constant across regions) as well as time trends that my be common to all regions. This already captures several factors that could not be accounted for at the country panel analysis. Column (3) further adds a control for income per capita to capture the stage of development of the region relative to the other regions in the country. Column (4) has three more demographic controls, i.e., mortality rates, life expectancy and fertility rates that may capture a long lasting effect on the incentives of individuals to invest in education and on their ability to invent. Column (5) augments the set of controls with the fraction of the working age population that have tertiary education to account for differences in the educational level across regions. The list of time varying controls that are available at the regional level is smaller than in the county panel analysis. However, this captures many more unobserved heterogeneity due to the presence of NUTS 2 effects.

Comparing the results of the regional analysis to the baseline estimation we conclude that accounting for the full set of available controls and fixed effects, the peak of the OADR is a bit higher than in the cross country analysis, i.e., approximately 35. This can be attributed to the fact that some countries with high rates of innovation, such as Japan, are not part of the sample. Another important element of this analysis is that in spite of much less variation of the OADR across regions and, more importantly, across time (recall that now the analysis is conducted for the period 2001-2012 where the changes are not as pronounced as for the period 1960-2012) we nevertheless obtain significant and consistent results even when accounting for NUTS 2 regional fixed effects.

5 Discussion

This section discusses several issues of interest related to our findings.

5.1 Population Aging and Innovating Sectors

Is the effect of population aging on inventive activity hump-shaped if we switch from the country level to the level of particular innovating sectors? This section establishes a hump-shaped effect for a subset of innovating sectors.

As in our baseline regressions, we analyze a sample of 33 OECD countries. We consider the period 1979-2011 for which the OECD statistics provide data on 12 distinct sectors. Our findings are shown in Table 10.

[TABLE 10 ABOUT HERE]

The dependent variable is now patent applications in each sector per 10,000 inhabitants. Column (1) illustrates the results for the aggregate number of patents using the full set of controls as in our baseline analysis above. The results are significant at the 5% level. In Column (2) - (6) of Panel A, the OADR has a significant effect on most of the sectors (with the exception of Biotechnology). In Columns (1) - (6) of Panel B, population aging does not confer any significant effect on inventive activity, not even in sectors that one would have anticipated such as the pharmaceutical or the medical sector.

There are at least two reasons why these findings are of interest. First, population aging has no effect on sectors related to improvements in medical technology or in technology that can prolong the life of individuals. This finding further mitigates potential concerns about reverse causality of medical innovations on population aging. Second, the fact that the OADR has an effect on sectors such as nanotechnology, physics or chemistry potentially indicates that population aging has an effect on inventive activity via fostering technical change. The peak of the hump, if it exists, may occur at a wide range of values.

5.2 Demographic Structure, Pension Scheme, Retirement Age and R&D

Consider Table 11 where we use the same set of controls as in the baseline model in all columns. In Column (1) the main explanatory variable for inventive activity is the fraction of the old aged 65 and above to the total population (as opposed to the working age population). According to the summary statistics of the sample this fraction varies from 0.33 to 24.4. The results remain quite strong and significant at the 5% level. The peak of the hump occurs at the level of 17.95 old people per 100 members of the total population. Not surprisingly, this number is smaller than the estimated level of the OADR that delivers the peak in our baseline regressions.[15]

[TABLE 11 ABOUT HERE]

Column (2) conducts a "placebo" test using the youth dependency ratio, i.e., the ratio of the young population below the age of 16 to the working age population aged 15-64. The purpose is to explore whether our main result is truly driven by the presence of the old or whether there is something related to the structure of the population that is being masked by the old-age dependency ratio. Interestingly, we find that none of the two terms comes out as significant. This suggests that our main finding does not operate via the demographic structure of the population or via the fraction of the future OADR, i.e., the current young.[16] On the contrary, it is the presence of the old that triggers our results. Columns (1) and (2) also capture the life-cycle hypothesis by accounting for the structure of the population.

Column (3) explores the role of the pension system. Using several OECD sources we construct a dummy variable that takes on the value of 1 if the pension system is a Pay-As-You-Go (PAYG) system and a value of 0 in all other cases that include fully-funded, partially funded, book reserved schemes, or any combination of these. The data are constructed using the type of pension scheme in the year 2013. The reason for structuring our variable in such a way is that a PAYG system imposes a direct burden on the young people in working age. Under this system it is reasonable to believe that the problem of aging is perceived by the young in a more transparent way than in alternative pension scheme.

We interact this dummy with the OADR and its squared term. Interestingly, our results indicate that the interaction terms come out as highly significant. Thus suggests that the results are more pronounced in the presence of the PAYG. The peak of the hump now occurs at a level of 27.3 which is similar to the one obtained in the baseline regression.

Column (4) explores whether our main result hinges on the country-specific retirement age of individuals. Our variable "Retirement Age" is constructed using several OECD sources. It takes on the value of 0 if the retirement age is below 63 and the value of 1 otherwise. The

[15] To relate the level of 17.95 to the level of the old-age dependency ratio of 25.1 that delivers the peak in our baseline regression (see Figure 4) note that both numbers are closely related. To see this, denote the fraction of the old in the total population at t by OTP_t, the total population in working age at t by L_t, and the total population at t by N_t. Then, $OTP_t \equiv L_{t-1}/N_t$. Moreover, with L_{t+1} denoting kids alive at t we have $N_t \equiv L_{t-1} + L_t + L_{t+1}$. Hence,

$$OTP_t = OADR_t \times \frac{L_t}{N_t} = OADR_t \times WTP_t$$

where WTP_t is the fraction of people in working age in the total population. Then, the peak values of the OTP and the OADR imply a corresponding value $WTP = 17.95/25.1 = 0.715$.

[16] Using the notation of Footnote 15 the young-age dependency ratio at time t is defined as $YADR_t = L_{t+1}/L_t = 1/OADR_{t+1}$.

data is derived from 2013 OECD reports. We use a dummy variable since there are several exceptions to the general rules defining the retirement age, and moreover, there are differences for men and women. Overall, we aimed at minimizing the level of errors. As shown in Column (4), none of the interaction terms come out as significant. This suggests that the retirement age confers no significant effect on our main result.

Finally, Column (5) addresses potential concerns on the measure of inventive activity employed. For this purpose we use an alternative measure, namely the number of researchers employed in R&D per one million people. For reasons of data limitations our sample has 32 OECD countries for the period 1997-2010. Reassuringly, our main findings remain highly significant. The implied peak of the hump occurs now at an OADR of roughly 26.2. This result is interpreted not only as a robustness check on the dependent variable, but can also indicate one potential channel via which aging affects inventive activity due to policy considerations. The number of researchers employed in R&D heavily relies on policy decisions related to the funding of R&D activities. We thus infer that in the face of aging, policy becomes more R&D oriented.

6 Concluding Remarks

This paper explores the intricate relationship between population aging and inventive activity. We empirically establish a hump-shaped effect of population aging on inventive activity. We attribute the increasing part of the hump to a rising acknowledgement in aging populations that inventive activity is necessary to keep the standards of living at current levels for both the economically dependent old and for the supporting working young. We attribute the decreasing part of the hump to Sauvy's conjecture according to which old societies lose the spirit of enterprise and the willingness to take risks. In our panel, the interplay of these two opposing forces gives rise to a hump with an estimated peak at an OADR between 24 and 27.

As a caveat, let us re-iterate that our analysis identifies the reduced form relationship between population aging and inventive activity. Ideally, one would also inquire more specifically into the explicit mechanisms that are behind this aggregate hump-shaped effect. We make one step in this direction in our companion paper (Irmen and Litina, 2017a), where we estimate the effect of population aging on individual attitudes towards new ideas and risk. We find this effect to be hump-shaped, too. Hence, even from this perspective, it is highly questionable that Sauvy's conjecture is a valid overall description for the relationship between population aging and inventive activity.

TABLES AND FIGURES

The following pages present all tables and figures referred to in the main text.

Table 1: Summary Statistics

	Obs	Mean	Std.	Min	Max
Patents per 1000 Inh.	1225	0.281	0.472	0.001	3.028
OADR per 100 Inh.	1225	18.685	5.770	5.951	39.043
Income Per Capita	1225	23,706.73	14,396.6	1106.754	86,127.24
Institutional Quality	1225	8.466	4.0255	-9	10
Urbanization Rate	1225	1.298	1.215	-2.051	7.543
Mortality Rate	1225	125.393	48.107	54.234	354.973
Life Expectancy	1225	74.541	5.189	47.574	83.096
Fertility Rate	1225	2.060	0.9384	1.076	6.777
Trade Flows as % of GDP	1225	68.031	42.568	8.333	349.849
GNE as % of GDP	1225	99.572	6.337	67.113	124.5386

Table 2: Summary Statistics

	Patents.	OADR	Income p.c.	Inst.	Urbanization	Mortality	Life Exp.	Fertility	Trade Flows	GNE
Patents per 1000 Inh.	1									
OADR per 100 Inh.	0.1594	1								
Income Per Capita	0.2046	0.6098	1							
Institutional Quality	0.1548	0.5389	0.4424	1						
Urbanization Rate	-0.1383	-0.6715	-0.2899	-0.5077	1					
Mortality Rate	-0.2851	-0.6198	-0.6428	-0.5413	0.4977	1				
Life Expectancy	0.2871	0.6692	0.6368	0.5192	-0.579	-0.941	1			
Fertility Rate	-0.2128	-0.6389	-0.4415	-0.5654	0.7562	0.6847	-0.7706	1		
Trade Flows as % of GDP	-0.163	0.2833	0.4478	0.2309	-0.2504	-0.2435	0.2871	-0.3488	1	
GNE as % of GDP	-0.1	-0.1569	-0.6156	-0.1776	0.1432	0.2649	-0.2621	0.2135	-0.5573	1

Table 3: The Effect of Population Aging on Inventive Activity - Baseline Regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Dependent Variable: Patents per 1000 Residents						
OADR	0.342***	0.264***	0.260***	0.248***	0.260***	0.258***	0.251***
	(0.120)	(0.079)	(0.080)	(0.079)	(0.080)	(0.079)	(0.082)
$(\text{OADR})^2$	−0.007**	−0.005***	−0.005***	−0.005***	−0.005***	−0.005***	−0.005***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Log Income per Capita		0.624***	0.547***	0.535***	0.541***	0.551***	0.565***
		(0.111)	(0.111)	(0.113)	(0.110)	(0.106)	(0.107)
Mortality Rate			-0.003	-0.003	-0.003	-0.003	-0.003
			(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Life Expectancy			−0.029*	-0.024	−0.028*	−0.028*	−0.029*
			(0.015)	(0.015)	(0.016)	(0.016)	(0.016)
Fertility Rate			-0.038	-0.008	-0.034	-0.034	-0.037
			(0.046)	(0.056)	(0.063)	(0.064)	(0.064)
Urbanization Rate				-0.036	-0.036	-0.036	-0.030
				(0.023)	(0.023)	(0.024)	(0.024)
Institutional Quality					-0.010	-0.010	-0.010
					(0.007)	(0.007)	(0.007)
GNE as % of GDP						0.001	-0.000
						(0.004)	(0.004)
Trade Flows as % of GDP							−0.002*
							(0.001)
Country & Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Period	1960-2012						
No of Countries	33	33	33	33	33	33	33
R-squared	0.523	0.642	0.649	0.655	0.664	0.664	0.668
Peak of the Hump	24.42	26.4	26	24.8	26	25.8	25.1

Summary: The table establishes the hump-shaped effect of population aging on inventive activity. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

TABLE 4: The Effect of Population Aging on Inventive Activity - IV Estimates

	(1)	(2)	(3)	(4)
	OLS	First Stage		2SLS
Dependent Variable:	Patents	OADR	$(\text{OADR})^2$.	Patents
Measles Immunization		0.155***	6.645***	
		(0.036)	(1.791)	
$(\text{OADR})^2$ Predicted		0.094***	-3.672***	
		(0.028)	(1.387)	
OADR	0.276***			0.288***
	(0.078)			(0.095)
$(\text{OADR})^2$	−0.005***			−0.005***
	(0.001)			(0.002)
Country-Year FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
F-Statistic				15.77
Time Period	1980-2010			
No of Countries	33	33	33	33
Peak of the Hump	27.5			28.8

Summary: This table establishes a causal effect of population aging on inventive activity using an IV analysis. The fraction of children aged 1-3 that is immunized against measles is used to instrument for the OADR. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) to obtain the predicted old-age dependency ratio we regress the OADR on the fraction of children immunized against measles while including all second-stage controls. This delivers predicted values of the old-age dependency ratio. The predicted old-age dependency ratio from the first stage is then squared. Finally, this squared term is used as an excluded instrument in the second stage along with the instrument "rates of immunization against measles"; (iv) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (v) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Robustness

Table 5: Robustness - External Validity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent Variable: Patents per 1000 Residents							
	World	Non OECD	Life Expectancy			Birth Rate		
			>50 years	>60 years	>70 years	<4 children	<3 children	<2 children
OADR	0.105^{*}	0.008^{*}	0.110^{*}	0.127^{**}	0.178^{**}	0.156^{**}	0.189^{***}	0.246^{***}
	(0.057)	(0.005)	(0.058)	(0.061)	(0.074)	(0.070)	(0.070)	(0.071)
$(\text{OADR})^2$	-0.002^{*}	-0.000^{**}	-0.002^{*}	-0.002^{*}	-0.003^{**}	-0.003^{**}	-0.003^{***}	-0.005^{***}
	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Country and Year FE	Yes	Yes	Yes					
Controls	Yes	Yes	Yes					
Time Period	1960–2012							
No of Countries	123	90	116	109	83	104	93	60
R-squared	0.329	0.197	0.345	0.374	0.391	0.378	0.442	0.536
Peak of the Hump	26.25	-	27.5	31.75	29.66	26	31.5	24.6

Summary: This table establishes the validity of our main result for different samples. Column (1) uses a world sample, Column (2) uses a sample of non-OECD countries. Columns (3) - (5) are based on samples of countries where life expectancy is higher than 50 years, higher than 60 years, or higher than 70 years, respectively. Columns (6) - (8) employ samples with a birth rate lower than 4, 3, and 2 children per women, respectively. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

TABLE 6: Robustness - Alternative Specifications I

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Dependent Variable: Patents per 1000 Residents						
	Lagged Aging	5-Year Lead	First Diffs	Dynamic Panel (1 Lag)	Time Trends	3-Year Aggr.	5-Year Aggr.
OADR Lag	0.261***	0.191***			0.250***	0.234***	0.222***
	(0.086)	(0.068)			(0.056)	(0.081)	(0.084)
$(OADR)^2$ Lag	−0.005***	-0.002**			-0.006***	-0.004***	-0.004*)
	(0.002)	(0.001)			(0.001)	(0.002)	(0.002)
OADR Diff.			0.165***				
			(0.064)				
$(OADR)^2$ Diff.			−0.003***				
			(0.001)				
OADR				0.009*			
				(0.004)			
$(OADR)^2$				−0.0002**			
				(0.000)			
Patents Lag				0.957***			
				(0.014)			
Country and Year FE	Yes		Yes	Yes	Yes	Yes	Yes
Controls	Yes		Yes	Yes	Yes	Yes	Yes
Time Period				1960–2012			
No of Countries	33	33	33	33	33	33	33
R-squared	0.667	0.618	0.132	0.976	0.892	0.660	0.667
Peak of the Hump	26.1	47.7	26	22.5	20.8	29.25	27.7

Summary: This table establishes that our main result is robust to a number of alternative estimators and specifications. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Table 7: Robustness - Alternative Specifications II

	(1)	(2)
	Dependent Variable: Patents per 1000 Residents	
	Linear	Cubic
OADR	0.020	0.603***
	(0.013)	(0.171)
$(\text{OADR})^2$		−0.021***
		(0.007)
$(\text{OADR})^3$		0.000**
		(0.000)
Country and Year FE	Yes	Yes
Controls	Yes	Yes
Time Period	1960–2012	
No of Countries	33	33
R-squared	0.469	0.703

Summary: This table explores whether other functional forms may explain the data. The specification of Column (1) is linear whereas the specification in Column (2) is cubic. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Table 8: Robustness - Additional Controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Dependent Variable: Patents per 1000 Residents						
OADR	0.382***	0.366***	0.357***	0.384***	0.363***	0.243***	0.345***
	(0.080)	(0.071)	(0.073)	(0.076)	(0.075)	(0.062)	(0.080)
$(OADR)^2$	−0.007***	−0.007***	−0.007***	−0.007***	−0.007***	-0.005***	−0.006***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)
Population Density	-0.002						-0.001
	(0.001)						(0.001)
Secondary Enrollment		0.001					0.001
		(0.002)					(0.002)
ICRG Corruption			0.014				-0.017
			(0.028)				(0.024)
Unemployment				0.010			-0.003
				(0.007)			(0.007)
Immigration Stocks					0.004		0.018
					(0.011)		(0.013)
Tertiary Education						-0.001	-0.001
						(0.002)	(0.002)
Country and Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Period	1985-2010 (5 year intervals)						
No of Countries	33	33	33	33	33	33	33
R-squared	0.825	0.822	0.822	0.826	0.821	0.705	0.724
Peak of the Hump	27.28	26.14	25.5	27.42	25.92	24.3	28.7

Summary: This table establishes that our main result is robust to the extension of our set of controls. The regressions in the table augment the baseline model by validating population density, secondary school enrollment, ICRG corruption, unemployment and immigration flows. These controls are added to the baseline controls that include log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure, international trade flows both as a % of GDP, time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Table 9: The Effect of Population Aging on Inventive Activity - Regional Analysis (NUTS 2)

	(1)	(2)	(3)	(4)	(5)
	Dependent Variable: Patents per 1000 Residents				
OADR	3.879***	2.129***	2.146***	2.462**	2.395**
	(0.569)	(0.776)	(0.758)	(1.077)	(1.033)
$(OADR)^2$	−7.293***	−2.852**	−2.879**	−3.481**	−3.481**
	(1.050)	(1.197)	(1.177)	(1.718)	(1.715)
Region FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Time Period	2001-2012				
No of Obs	2842	2842	2842	2842	2842
R-squared	0.009	0.746	0.746	0.746	0.746
Peak of the Hump	26.59	37.32	37.27	35.34	34.40

Summary: The table establishes the hump-shaped effect of population aging on inventive activity at the regional NUTS 2 level. The analysis controls for log income per capita, life expectancy, fertility and mortality rates and the fraction of the working age population that have tertiary education. All regressions feature time and regional fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64; (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) robust standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Discussion

TABLE 10: The Effect of Population Aging on Inventive Activity - OECD Innovation Sectors

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent Variable: Number of Patent Per 10,000 Inhabitants - Panel A					
	Total	Nanotechnology	Biotechnology	Chemistry	Physics	Electricity
OADR	0.134**	0.003***	0.005	0.022***	0.052***	0.066***
	(0.063)	(0.001)	(0.004)	(0.007)	(0.018)	(0.022)
$(OADR)^2$	−0.003*	−0.000***	−0.000	−0.000***	−0.001***	−0.001***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.783	0.638	0.692	0.678	0.732	0.553
Peak of the Hump	22.3	-	-	-	26	33
	Dependent Variable: Number of Patent Per 10,000 Inhabitants - Panel B					
	Medical	Pharmacheutical	Human	Performing	Textiles	Mechanical
OADR	-0.011	-0.001	-0.010	0.005	0.001	0.002
	(0.007)	(0.004)	(0.013)	(0.012)	(0.003)	(0.011)
$(OADR)^2$	0.000	-0.000	0.000	-0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.678	0.647	0.731	0.707	0.147	0.531
Country & Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Time Period	1979-2010					
No of Countries	33	33	33	33	33	33
Peak of the Hump	-	-	-	-	-	-

Summary: The table employs an OECD sample of 33 countries to study the effect of population aging on inventive activity in different innovating sectors. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age; (ii) "Patents per sector and per 10,000 residents" is measured as the number of patent applications filed in a sector per 10,000 residents; (iii) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (iv) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

Table 11: The Effect of Population Aging on Inventive Activity - Demographic Structure, Pension Scheme and Retirement Age

	(1)	(2)	(3)	(4)	(5)
Dependent Variable:	Patents per 1000 Residents				Researchers in R&D
Old Above 65 Ratio	0.359**				473.039**
	(0.135)				(190.409)
(Old Above 65 Ratio)^2	−0.010**				-8.976**
	(0.004)				(3.344)
Young Dependency Ratio		-0.016			
		(0.014)			
(Young Dependency Ratio)^2		0.000			
		(0.000)			
OADR			0.041	0.381**	
			(0.036)	(0.152)	
(OADR)^2			-0.001	-0.009**	
			(0.001)	(0.004)	
OADR $\times$ Pension Scheme			0.328***		
			(0.061)		
(OADR)$^2\times$ Pension Scheme			-0.006***		
			(0.001)		
OADR $\times$ Retirement Age				-0.142	
				(0.165)	
(OADR)$^2\times$ Retirement Age				0.005	
				(0.003)	
Country & Year FE	Yes				
Time Period	1960-2012				1997-2010
No of Countries	33				32
R-squared	0.653	0.345	0.789	0.693	0.691
Peak of the Hump	17.9	-	27.3	21.16	26,36

Summary: The table discusses several issues of interest related to our main result of a hump-shaped relationship between populaton aging and inventive activity. Column (1) employs the fraction of the old to the total population as the explanatory variable. The explanatory variable in Column (2) is the young dependency ratio. Column (3) interacts the OADR with the type of retirement system. Column (4) interacts the OADR with a threshold level for the retirement age. Column (5) employs as a proxy for inventive activity the number of researchers employed in R&D. The analysis controls for log income per capita, life expectancy, fertility and mortality rates, the urbanization rate, institutional quality, gross national expenditure and international trade flows both as a % of GDP. All regressions feature time and country fixed effects.

Notes: (i) The old above 65 ratio is measured as the number of people above the age of 65 as a fraction of the total population. The old-age dependency ratio is the ratio of population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age. The youth dependency ratio is the ratio of individuals less than 16 to the total working age population (aged 15-64); (ii) "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents; (iii) *Retirement System* is a dummy variable that takes on the value of 1 if the pension system in the country is PAYG and 0 otherwise; (iv) *Retirement Age* is a dummy variable that takes on the value of 1 if retirement age is above 63 and 0 otherwise; (v) standard errors are clustered at the country level; robust and clustered standard errors are reported in parentheses; (vi) *** denotes statistical significance at the 1 percent level, ** at the 5 percent level, and * at the 10 percent level, all for two-sided hypothesis tests.

References

Daron Acemoglu and Pascual Restrepo. Secular stagnation? the effect of aging on economic growth in the age of automation. Technical report, National Bureau of Economic Research, 2017.

David Bloom and Alfonso Sousa-Poza. Ageing and Productivity: Introduction. *IZA Discussion Papers, No. 7205*, February 2013.

Axel H Börsch-Supan. Policy Mixes in the Current European Pension Reform Process. *DICE Report*, 10(4):9, 2012.

Jie Cai and Andrey Stoyanov. Population Aging and Comparative Advantage. *Journal of International Economics*, 102:1–21, 2016.

In Choi. Unit Root Tests for Panel Data. *Journal of International Money and Finance*, 20(2):249–272, 2001.

Luiz de Mello, Simone Schotte, Erwin R. Tiongson, and Hernan Winkler. Greying the Budget: Ageing and Preferences over Public Policies. *Kyklos*, 70(1):70–96, 2017.

Stefano DellaVigna and Joshua M Pollet. Demographics and industry returns. *The American Economic Review*, 97(5):1667–1702, 2007.

James Feyrer. Demographics and Productivity. *The Review of Economics and Statistics*, 89(1):100–109, 2007.

Martín Gonzalez-Eiras and Dirk Niepelt. Ageing, Government Budgets, Retirement, and Growth. *European Economic Review*, 56(1):97–115, 2012.

Robert J Gordon. *The Rise and Fall of American Growth: The US Standard of Living Since the Civil War*. Princeton University Press, 2016.

Diane E. Griffin. *Measles Virus*. In: Wiley Encyclopedia of Molecular Medicine, John Wiley and Sons, Inc., 2002.

Burkhard Heer and Andreas Irmen. Population, Pensions, and Endogenous Economic Growth. *Journal of Economic Dynamics and Control*, 46:50–72, 2014.

Andreas Irmen and Anastasia Litina. Population Aging and Inventive Activity. *CESifo Working Paper No. 5841, CESifo Munich*, 2016b.

Andreas Irmen and Anastasia Litina. What a Study of 33 Countries Found About Aging Populations and Innovation. *Harvard Business Review (https://hbr.org/2017/01/what-a-study-of-33-countries-found-about-aging-populations-and-innovation)*, 2017.

Andreas Irmen and Anastasia Litina. Population Aging and Culture: Do Old Societies Think Old Ideas? *mimeo, Center for Research in Economic Activity (CREA), University of Luxembourg*, 2017a.

Andreas Irmen. Capital-and Labor-Saving Technical Change in an Aging Economy. *International Economic Review*, 58(1):261–285, 2017.

Ruth A. Judson and Ann L. Owen. Estimating Dynamic Panel Data Models: A Guide for Macroeconomists. *Economics Letters*, 65(1):9–15, October 1999.

Tomas Kogel. Youth Dependency and Total Factor Productivity. *Journal of Development Economics*, 76(1):147–173, 2005.

Johanna Kuehnel. Population Aging, the Composition of Government Spending, and Endogenous Economic Growth in Politico-Economic Equilibrium. *in: Essays on the Theory of Productive Government Activity and Economic Growth, Chapter 4, PhD Dissertation, University of Heidelberg*, 2011.

Mariano Kulish, Christopher Kent, and Kathryn Smith. Aging, retirement, and savings: A general equilibrium analysis. *The BE Journal of Macroeconomics*, 10(1), 2010.

Nicole Maestas, Kathleen J Mullen, and David Powell. The Effect of Population Aging on Economic Growth, the Labor Force and Productivity. Technical report, National Bureau of Economic Research, 2016.

Gabriele Marconi. Education as a Long-Term Investment: The Decisive Role of Age in the Education-Growth Relationship. *Kyklos*, 71(1):132–161, 2018.

Stephen J. Nickell. Biases in Dynamic Models with Fixed Effects. *Econometrica*, 49(6):1417–26, November 1981.

MH Pesaran. General Diagnostic Tests for Cross Section Dependence in Panels. *IZA Discussion Papers, No. 1240*, 2004.

James Poterba. Retirement Security in an Aging Population. *The American Economic Review*, 104(5):1–30, 2014.

Bernd Rechel, Yvonne Doyle, Emily Grundy, and Martin McKee. How Can Health Systems Respond to Population Ageing? *World Health Organisation, Policy Brief 10.*, 2009.

Alfred Sauvy. Social and Economic Consequences of the Ageing of Western European Populations. *Population Studies*, 2(1):115–124, 1948.

Otto Toivanen and Lotta Väänänen. Education and Invention. *Review of Economics and Statistics*, 98(2):382–396, 2016.

David Weil. The Economics of Population Aging. *In Handbook of Population and Family Economics, Elsevier*, 1:967–1014, 1997.

Jeffrey M Wooldridge. *Econometric Analysis of Cross Section and Panel Data*. MIT press, Cambridge, Massachusetts. London, England, 2010.

Appendix: Variable Definitions and Sources

A. World Bank Indicators and Aggregate Data

Patent Applications. Patent applications are worldwide patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office for exclusive rights for an invention–a product or process that provides a new way of doing something or offers a new technical solution to a problem. A patent provides protection for the invention to the owner of the patent for a limited period, generally 20 years. "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents. The source of the data is the World Development Indicators and the World Intellectual Property Organization (WIPO).

Researchers in Research and Development. Researchers in R&D are professionals engaged in the conception or creation of new knowledge, products, processes, methods, or systems and in the management of the projects concerned. Postgraduate PhD students (ISCED97 level 6) engaged in R&D are included. The source of the data is the World Development Indicators.

Old Age Dependency Ratio (OADR). The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64 stated as the number of dependents per 100 persons of working age. The source of the data is the World Development Indicators.

Fraction of Old above 65. The old above 65 ratio is measured as the number of people above the age of 65 as a fraction of the total population. The quadratic term is the squared term of the fraction of old. The source of the data is the World Development Indicators.

Youth Dependency Ratio. The youth dependency ratio is the ratio of individuals less than 16 to the total working age population (aged 15-64). The source of the data is the World Development Indicators.

GDP per Capita. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2005 U.S. dollars. Dollar figures for GDP are converted from domestic currencies using 2000 official exchange rates. The source of the data is the World Development Indicators.

Mortality Rate. Adult mortality rate is the probability of dying between the ages of 15 and 60–that is, the probability of a 15-year-old dying before reaching age 60, if subject to current age-specific mortality rates between those ages. The reported values is the mean mortality rate for men and women. The source of the data is the World Development Indicators.

Life Expectancy. Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life. The source of the data is the World Development Indicators.

Fertility Rates. Total fertility rate represents the number of children that would be born to a woman if she were to live to the end of her childbearing years and bear children in accordance with current age-specific fertility rates. The source of the data is the World Development Indicators.

Urbanization Rate. Urban population refers to people living in urban areas as defined by national statistical offices. It is calculated using World Bank population estimates and urban ratios from the United Nations World Urbanization Prospects.

Institutional Quality. The source of the data is the POLITY IV dataset and measures the level of democracy for all independent states. The variable takes values from -10(dictatorship) to 10 (democracy).

Gross National Expenditure. Gross national expenditure (formerly domestic absorption) is the sum of household final consumption expenditure (formerly private consumption), general government final consumption expenditure (formerly general government consumption), and gross capital formation (formerly gross domestic investment). Data are expressed as a % of GDP. The source of the data is the World Development Indicators.

Trade Flows. The source of the data is the WDI and it is the sum of exports and imports of goods and services measured as a share of gross domestic product.

Measles Immunization. Child immunization against measles is the fraction of children aged 12-23 months who received a vaccination before their 12th month. A child is considered adequately immunized against measles after receiving one dose of vaccine. The source of the data is the World Development Indicators.

Retirement System. Using several OECD sources we construct a dummy variable that takes the value of 1 if the pension system is a Pay-As-You-Go (PAYG or unfunded) system and 0 in any other case (fully funded, partially funded, book reserved or any other combination). The data are constructed using the type of pension system as of the year 2005. The definitions for each funding scheme, as derived by the 2005 OECD report on the classification and glossary of private pensions (http://www.oecd.org/finance/private-pensions/38356329.pdf, accessed on July, 21st, 2015), are the following :

Unfunded pension plans: plans that are financed directly from contributions from the plan sponsor or provider and/or the plan participant. Unfunded pension plans are said to be paid on a current disbursement method (also known as the pay-as-you-go, PAYG, method). Unfunded plans may still have associated reserves to cover immediate expenses or smooth contributions within given time periods.

Funded (fully or partially) pension plans: occupational or personal pension plans that accumulate dedicated assets to cover the plan's liabilities. These assets are assigned by law or contract to the pension plan. Their use is restricted to the payment of pension plan benefits.

Book reserved pension plans: sums entered in the balance sheet of the plan sponsor as reserves or provisions for occupational pension plan benefits. Some assets may be held in separate accounts for the purpose of financing benefits, but are not legally or contractually pension plan assets.

Retirement Age. Our variable on the retirement age is constructed using several OECD sources and takes the value of 0 if retirement age is below 63 and 1 otherwise (http://www.oecd.org/pensions/public-pensions/OECDPensionsAtAGlance2013.pdf, , accessed on July, 21st, 2015).

Population Density. Population density is a measure of population per unit area. The source of the data is the World Development Indicators.

School Enrolment. School enrolment ratio is the total enrollment in secondary education, regardless of age, expressed as a percentage of the population of official secondary education age. This variable can exceed 100% due to the inclusion of over-aged and under-aged students because of early or late school entrance and grade repetition. The source of the data is the World Development Indicators.

ICRG Corruption. A measure of corruption constructed by the PRS group. It takes values between - and 6 with 6 denoting the most corrupt country.

Unemployment. Unemployment refers to the share of the labor force that is without work but available for and seeking employment. Definitions of labor force and unemployment differ by country. The source of the data is the World Development Indicators.

Immigration Stocks. It measures the total migrant stocks residing in each OECD country. The source of the data is the World Development Indicators and they are available for every 5 year intervals. The source of the data is the World Development Indicators.

Tertiary Education. Tertiary education is the gross enrollment ratio in tertiary education of both sexes. The source of the data is the World Development Indicators

B. OECD Data

OECD Patent Applications. Patent applications are worldwide patent applications filed through the European Patent Office (EPO). The data are available from 1978 onwards. The measure is the total count of patents in each of the following sectors: Nanotechnology, Biotechnology, Chemistry, Physics, Electricity, Medical, Pharmaceutical, Human Necessities, Performing Operations, Textiles, Mechanical Engineering. The data are available from the OECD statistics. They are measured in per 10,000 residents units. A detailed description of each sector can be found at OECD 2008 Compendium of Patent Statistics (http://www.oecd.org/sti/inno/37569377.pdf, accessed on July, 21st, 2015) and at WIPO homepage (http://web2.wipo.int/ipcpub/#refresh=page, accessed on July, 21st, 2015).

C. NUTS 2 Regional Data

Patent Applications. Patent applications are worldwide patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office for exclusive rights for an invention–a product or process that provides a new way of doing something or offers a new technical solution to a problem. A patent provides protection for the invention to the owner of the patent for a limited period, generally 20 years. "Patents per 1000 residents" is measured as the number of patent applications filed per 1000 residents. The source of the data is Eurostat.

Old Age Dependency Ratio (OADR). The old-age dependency ratio is the ratio of the population aged 65 and over to the population 15-64. The source of the data is Eurostat..

Fraction of Old above 65. The old above 65 ratio is measured as the number of people above the age of 65 as a fraction of the total population. The quadratic term is the squared term of the fraction of old. The source of the data is the World Development Indicators.

Youth Dependency Ratio. The youth dependency ratio is the ratio of individuals less than 16 to the total working age population (aged 15-64). The source of the data is the World Development Indicators.

GDP per Capita. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. The source of the data is Eurostat.

Mortality Rate. Adult mortality rate is the total number of deaths at the regional level. The source of the data is Eurostat.

Life Expectancy. Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life. The source of the data is Eurostat..

Fertility Rates. Total fertility rate represents the number of children that would be born to a woman if she were to live to the end of her childbearing years and bear children in accordance with current age-specific fertility rates. The source of the data is Eurostat.

Tertiary Education. Tertiary education is the fraction of men and women that are enrolled in tertiary education. The source of the data is Eurostat.