Returns to ICT Skills*

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Abstract

How important is mastering information and communications technology (ICT) in modern labor markets? Previous research offers no guidance in assessing the labor-market returns to ICT skills, primarily because skill data have been unavailable. We draw on unique data that provide internationally comparable information on ICT skills in 19 countries. Using an instrument that leverages cross-country variation in the technologically determined probability of having Internet access, we find that ICT skills are substantially rewarded in the labor market. Placebo estimations show that exogenous Internet availability cannot explain numeracy or literacy skills, suggesting that our identifying variation is independent of a person's general ability. We also exploit peculiarities in the structure of the pre-existing voice-telephony network across German municipalities, confirming the findings from the cross-country analysis.

Keywords: ICT skills; broadband; labor market; earnings; international comparisons

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1. Introduction

"The new literacy" is the notion that Neelie Kroes, Vice President of the European Commission, uses to describe an individual's skill to master information and communication technology (ICT). She justifies this powerful choice of words by arguing that "the online world is becoming a bigger part of everything we do. No wonder these [ICT] skills are becoming central in the job market."[1] Even though this argument appears convincing at first glance, empirical evidence on the effects of ICT skills on labor-market outcomes has yet to be provided. The main reason for this lack of research is the unavailability of data to measure ICT skills consistently within and across countries, and to capture variation in an individual's ICT skills that is unrelated to other domains of cognitive skills. Using internationally comparable data on individuals' ICT skills in 19 countries, this paper is the first to provide a rigorous empirical assessment of the wage returns to ICT skills.

Our main data source is the Programme for the International Assessment of Adult Competencies (PIAAC). PIAAC is the first-ever study that assessed individuals' ICT skills (called "problem-solving in technology-rich environments" in PIAAC). The survey was conducted between August 2011 and March 2012 in 24 developed countries, which represent about 75 percent of the worldwide GDP.[2] PIAAC was designed to provide representative measures of cognitive skills possessed by adults aged 16 to 65 years in three different domains (i.e., numeracy, literacy, and ICT). Having skill data from various domains offers a unique opportunity to test the whether the estimated effect of ICT skills on wages just reflects a person's general ability.

Our identification strategy rests on the assumption that ICT skills are developed by performing ICT-related tasks. However, having access to the Internet is a precondition for this type of learning-by-doing. We thus exploit exogenous variation in the probability of having access to the Internet in a cross-country instrumental-variable approach. This variation stems from international differences in the roll-out of the pre-existing fixed line voice-telephony network, which was upgraded in most countries to provide high-speed Internet access (Czernich, Falck, Kretschmer, and Woessmann, 2011). We further argue, and provide evidence, that individuals living in countries with a higher

[1] http://www.getonlineweek.eu/vice-president-neelie-kroes-says-digital-literacy-and-e-skills-are-the-new-literacy/; accessed March 16, 2015.

[2] ICT skills were tested in 20 of the 24 participating countries. We do not use data from the Russian Federation because data are not representative of the entire Russian population, as the population of the Moscow municipal area is not included (see Section 2 for details).

technologically determined probability of having access to the Internet develop ICT skills through learning-by-doing faster. Conditional on cross-country differences in the stage of economic development and in the spatial concentration before the first emergence of (fast) Internet, we can plausibly identify a causal impact of ICT skills on wages.

In addition to the cross-country instrumental-variable approach, we also exploit historical peculiarities in the layout of the pre-existing voice-telephony infrastructure within a single country, Germany. While the distance between a household and the main distribution frame is irrelevant for the quality of voice-telephony services, it restricts the maximum bandwidth of broadband Internet. After surpassing a certain distance threshold, high-speed Internet access is no longer feasible without substantial infrastructure investment, excluding a large share of West German municipalities from broadband Internet access (Falck, Gold, and Heblich, 2014). The technical threshold in the households' distance to the main distribution frame they are connected to provides exogenous variation in the availability of broadband Internet and, as a consequence, in ICT skills.

Our findings from both instrumental variable approaches indicate a positive effect of ICT skills on individual wages, which is both economically and statistically significant. In the cross-country analysis, a one-standard-deviation increase in ICT skills leads to a 17.1 percent increase in hourly wages. These estimates also control for a rich set of individual-level variables, including a person's acquired level of schooling. Our results further provide tentative support for the idea that returns to ICT skills are higher than returns to other skills, which is consistent with ICT skills being especially important in modern knowledge-based economies. Moreover, pre-existing fixed line diffusion is associated with no appreciable changes in numeracy and literacy skills, which we consider as strong evidence that our identification strategy isolates the effect of ICT skills (vis-à-vis generic skills) on wages. Another placebo test shows that our instrument is irrelevant in a sample of first-generation immigrants who are unlikely to have acquired ICT skills in the PIAAC test country. Further, we provide evidence for the learning-by-doing channel through which Internet access affects ICT skills by leveraging information in the PIAAC data on Internet use at home and at work. Finally, the pattern revealed by the within-country analysis supports the existence of substantial returns to ICT skills in the labor market, which are not confounded by a person's general ability.

Our paper adds to the recently emerging stream of literature that regards direct measures of cognitive skill as more reliable proxies for effective human capital than acquired years schooling (e.g., Hanushek and Kimko, 2000; Hanushek and Woessmann, 2008). However, existing literature offers little guidance in assessing the magnitude of the labor-market returns to cognitive skills, as most of the previous evidence stems from the small number of U.S. panel datasets that follow tested students into their initial jobs.[3] A noticeable exception is the work by Hanushek, Schwerdt, Wiederhold, and Woessmann (2015), who also draw on the PIAAC data to produce new international evidence on the wage returns to cognitive skills. However, the authors do not attempt to specifically investigate the returns to ICT skills, which is the aim of this study. Moreover, while exploring issues of causality by using several instrumental variable approaches, they exploited plausibly exogenous variation in skills only in the United States, using changes in compulsory schooling laws over time at the state level. However, this source of identifying variation is unlikely to be capable of discriminating between different types of skills. We contribute to the discussion about causality in the returns-to-skills estimation by assessing the role of domain-specific skills for labor-market outcomes. Moreover, instead of relying solely on within-country variation in skills, our identification strategy exploits exogenous variation both across and within countries.

Our paper is also related to the literature on the effects of ICT on productivity and growth. In a cross-country regression framework, Czernich, Falck, Kretschmer, and Woessmann (2011) find economically important effects of broadband infrastructure on growth in OECD economies. Since they exploit the same source of exogenous variation in broadband Internet access as we do in our cross-country analysis, we are likely identifying one of the channels through which broadband influences economic growth, namely, the productivity-enhancing effect of ICT skills acquired through learning-by-doing. This channel, however, had so far never been explicitly tested for. Recently, Akerman, Gaarder, and Mogstad (2015) have investigated the effect of firms' broadband adoption on employees' wages. Using rich Norwegian data, they find that broadband adoption benefits skilled workers because they are often engaged in non-routine abstract tasks, while unskilled workers performing routine tasks suffer wage losses. Our analysis complements their task-based approach in explaining labor-market effects of the adoption of broadband Internet as we can directly measure the response in ICT skills to broadband diffusion. We can also observe whether productivity-enhancing ICT skills can be learned through the frequent use of ICT-related tasks at work.

[3] Overviews of the existing evidence can be found in Bowles, Gintis, and Osborne (2001), Hanushek and Woessmann (2008), and Hanushek and Rivkin (2012).

The paper is organized as follows. Section 2 describes the PIAAC data and the measurement of ICT skills. Section 3 outlines our identification strategy. Section 4 presents the empirical results from the cross-country investigation, including Placebo tests and robustness checks. Section 5 presents our findings from the within-country analysis. Section 6 concludes.

2. ICT Skills

The unique feature of this paper is the application of new and consistent international data on ICT skills of the adult population. These data stem from the Programme for the International Assessment of Adult Competencies (PIAAC). PIAAC is the product of collaboration between participating countries through the Organization for Economic Co-operation and Development (OECD), and uses leading international expertise to develop valid comparisons of skills across countries and cultures. The survey was conducted between August 2011 and March 2012 in 24 countries, which represent about 75 percent of the worldwide GDP.[4] PIAAC was designed to provide representative measures of cognitive skills possessed by adults aged 16 to 65 years, and samples included at least 5,000 participants in each country. The countries used different sampling schemes in drawing their samples, but these were all aligned to known population counts with post-sampling weightings.

Together with information on cognitive skills, PIAAC also offers extensive information on respondents' individual and workplace characteristics, for instance, skill use at home and at work. This information is derived from a detailed background questionnaire completed by the PIAAC respondents prior to the skills assessment. The survey was administered by trained interviewers either in the respondent's home or in a location agreed upon between the respondent and interviewer.

PIAAC provides measures of cognitive skills in three domains: literacy, numeracy, and ICT (called "problem solving in technology-rich environments" in the survey). PIAAC measures each of

[4] Countries that participated in PIAAC are Australia, Austria, Belgium (Flanders), Canada, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Japan, Korea, the Netherlands, Norway, Poland, the Russian Federation, the Slovak Republic, Spain, Sweden, the United Kingdom (England and Northern Ireland), and the United States. Canada (November 2011 to June 2012) and France (September to November 2012) were the only countries with a different survey period.

the skill domains on a 500-point scale.[5] The individual-level correlation of ICT skills with literacy (numeracy) is 0.77 (0.73), which is less strong than the correlation between literacy and numeracy (0.82). Still, all three skill domains appear to measure distinct dimensions of a respondent's skill set.

We focus on ICT skills, defined as "using digital technology, communication tools and networks to acquire and evaluate information, communicate with others and perform practical tasks" (OECD, 2013, p. 86).[6] To assess ICT skills, participants were given a series of problem scenarios and had to find a solution to a problem using ICT-based applications such as an Internet browser and web pages, e-mail, word processing, and spreadsheet tools. Often, solving the tasks required to combine several applications, e.g., managing requests to reserve a meeting room using a web-based reservation system and send out e-mails to decline requests if reservation requests could not be accommodated.[7]

ICT skills were assessed in a computer-based mode, so some basic knowledge regarding the use of computers was required to participate in the ICT skill test. 9.3 percent of all PIAAC participants indicated in the background questionnaire that they had no prior computer experience; therefore, they did not take part in the computer-based assessment. Instead, they conducted the survey in pencil-and-paper mode, and only numeracy and literacy skills were tested. Participants who reported at least basic knowledge in computer-based applications were issued an ICT core test, which assessed the basic ICT competencies such as using a keyboard/mouse or scrolling through text on the screen. 4.9 percent of the participants did not pass this test and were also excluded from the ICT skills assessment. Finally, 10.2 percent of the participants opted to take the paper-based assessment without first taking the ICT core assessment, even though they reported some prior experience with computers.[8]

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[5] PIAAC provides 10 plausible values for each respondent and each skill domain. Throughout, we use the first plausible value of the PIAAC scores in each domain. See Perry, Wiederhold, and Ackermann-Piek (2014) for a discussion of the plausible values in PIAAC.

[6] *Literacy* is the ability to understand, evaluate, use and engage with written texts to participate in society, to achieve one's goals, and to develop one's knowledge and potential. *Numeracy* is the ability to access, use, interpret, and communicate mathematical information and ideas in order to engage in and manage the mathematical demands of a range of situations in adult life. See OECD (2013) for details.

[7] See OCED (2013, p. 89) for examples of problem scenarios used in PIAAC to test participants' ICT skills. The ICT tasks to be solved by participants came in three different difficulty levels.

[8] Not surprisingly, people who took the paper-based assessment are on average older than people who took the computer-based assessment, which holds for all three types (no computer experience, failed in core ICT test, opting out). People whose skills were assessed paper-based also use Internet and computers only very infrequently, if at all, at

In total, ICT skills could not be measured for about 24 percent of the population of PIAAC respondents. Persons without an ICT skills score are excluded from our sample. Moreover, the assessment of ICT skills was an international option. Cyprus, France, Italy, and Spain did not take part in the ICT skills assessment, leaving us with data for 19 countries.[9] For reasons related to our identification strategy (see Section 3), in our main analysis we will focus on 20-49 year old natives and second-generation immigrants. This leaves us with a total of 40,865 individual-level observations.

Figure 1 depicts average ICT skills by country. The average level of ICT skills is 294 points, with an individual-level standard deviation of about 40 points (see also Table A-1). Respondents in Japan, Sweden, and Finland have the highest average scores, while respondents in the former communist countries (Czech Republic, Poland, Slovak Republic), Estonia, and Ireland score lowest in the ICT skill assessment. The difference between Japan (being the best-performing country with 306 points) and Poland (being the worst-performing country with 276 points) amounts to almost 75 percent of a standard deviation.[10] For expositional purposes, we do not use raw scores in the subsequent regression analyses but standardize scores to have a mean of zero and standard deviation of one across countries.[11]

<< Figure 1 about here >>

Table A-1 shows the descriptive statistics of participants' characteristics for the pooled sample and separately for the 19 countries in the sample. The size of the estimation sample ranges from

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home. Moreover, they possess on average lower literacy and numeracy skills. See also OECD (2013) and Rammstedt (2013).

[9] In addition to the countries that did not test participants' ICT skills, we exclude the Russian Federation from the analysis. According to OECD (2013), data for the Russian Federation are preliminary, may still be subject to change, and are not representative of the entire Russian population because they do not include the population of the Moscow municipal area.

[10] Figure A-1, which shows the distribution of ICT skills within each country with the smoothed (kernel) fit for Japan for comparison, yields similar conclusions regarding the cross-country differences in ICT skills. We observe that the Nordic countries, especially Sweden and Finland, have very similar skill distributions as Japan, while the distributions in the post-communist countries, Estonia, Ireland are shifted to the left.

[11] In most empirical specifications we use the country-level standard deviation to standardize the skill test scores because our IV strategy relies on between-country variation.

1,375 persons in the Slovak Republic to 7,531 persons in Canada. The Canadian sample is much larger than those of any other PIAAC country due to oversampling to obtain regionally reliable estimates. Also apparent from Table A-1 are the substantial differences in hourly wages (in PPP-$) across countries.[12] Workers in Norway, Denmark, and Ireland earn highest wages and workers in the post-communist countries are paid lowest, with the difference between the highest-paying country (Norway) and lowest-paying country (Slovak Republic) amounting to 160 percent of an international standard deviation. There is also considerable cross-country variation in our estimation sample in years of schooling, work experience, gender composition, and the presence of children.

3. Estimation Strategy

We estimate returns to ICT skills in a general Mincer framework (Mincer 1970, 1974) that relates a person's human capital to earnings on the labor market. Specifically, we estimate the following individual-level wage regression:

$$w_{ic} = \beta_0 + \beta_1 ICT_{ic} + \beta_2 X_{ic} + \beta_3 X_c + \varepsilon_{ic}. \tag{1}$$

Here, w_{ic} is the log of gross hourly wages earned by individual i living in country c and ICT_{ic} are the individual's ICT skills. X_{ic} is a vector of individual-level variables including the "standard" Mincer controls (years of schooling, work experience, gender) and an indicator for the presence of children. X_c is a vector of country-level control variables, which we discuss in greater details below. ε_{ic} is a standard error term. The coefficient of interest is β_1. It shows the wage change in percent when ICT skills increase by one unit. Since ICT skills are *z*-standardized in the empirical analysis, β_1 is to be interpreted as the percentage increase in wages resulting from a one-standard-deviation increase in ICT skills.

In this basic regression framework, β_1 can hardly be interpreted as the causal effect of ICT skills on wages. The most obvious reasons for β_1 being a biased estimate of the true returns to ICT skills are measurement error and omitted variables. The problem of measurement error arises

[12] The PIAAC Public Use File reports hourly wages for Austria, Canada, Sweden, and the United States only as a worker's decile rank in the country-specific wage distribution. As in Hanushek, Schwerdt, Wiederhold, and Woessmann (2015), we obtain wage information in these countries by assigning the decile median of hourly wages to each survey participant belonging to the respective decile of the country-specific wage distribution. Moreover, in each country, we trim the bottom and top one percent of the wage distribution to limit the influence of outliers.

because cognitive skills in PIAAC may just be an error-ridden measure of the human capital relevant on the labor market (see Hanushek, Schwerdt, Wiederhold, and Woessmann, 2015, for a discussion). While this classical measurement error in the assessment of an individual's ICT skills will bias the coefficient on ICT skills towards zero, the direction of the omitted-variable bias is a prior not clear. If ICT skills as measured in PIAAC are correlated with other (partly unobserved) skills, β_1 will not measure the true returns to ICT skills but the average returns to a bouquet of individual skills. This estimate might be larger or smaller than the true effect of ICT skills on wages depending on whether ICT skills have larger or smaller returns than the other unobserved skills. Moreover, omitted-variable bias may also arise because unobserved variables like non-cognitive skills, personality traits, or family background could directly influence earnings and may also be related to ICT skills.

In order to solve these endogeneity problems, we apply two instrumental-variable (IV) strategies. The basic idea behind both of them is that individuals acquire ICT skills through learning-by-doing, while having access to the Internet is a precondition for this type of learning-by-doing. Our first and main IV strategy thus exploits exogenous variation in the probability of having access to the Internet across countries.[13] This variation stems from the extent of the pre-existing fixed-line voice-telephony network, which is upgraded in most countries to provide fast Internet access by means of the so-called DSL technology. This strategy has first been introduced into the economics literature by Czernich, Falck, Kretschmer, and Woessmann (2011). The authors estimate an S-shaped diffusion curve and show that countries with a farther-reaching voice-telephony network in 1996 (i.e., before the introduction of broadband Internet in any country) had higher diffusion rates of broadband Internet in any consecutive year. The non-linear diffusion curve is estimated in the following way:

$$B_{ct} = \frac{\gamma_c}{1 + \exp[-\beta(t - \tau)]} + \theta_{ct}, \qquad (2)$$

where B_{ct} is the diffusion of broadband in the population in country c at time t. γ_c determines the country-specific maximum penetration level of broadband diffusion (ceiling). β and τ denote the diffusion speed and the inflexion point of the diffusion process, respectively. Both variables are not

[13] Our within-country identification strategy for Germany (described in detail in Section 5) uses technical peculiarities of the historical German voice telephony network that limited the availability of high-speed Internet access as a source of identifying variation.

country-specific. θ_{ct} is a stochastic error term. γ_c is explained by the extent of the pre-existing voice-telephony network, T_c , which can be upgraded for Internet purposes:

$$\gamma_c = \gamma_0 + \alpha_1 T_c. \tag{3}$$

Figure 2 plots the actual and estimated broadband Internet diffusion curves across the 19 countries in our sample. Estimations are on the basis of ITU data on the broadband Internet diffusion between 1996 and 2012 and extent of the voice-telephony network in 1996.[14] The figure reveals that the estimated broadband Internet diffusion fits the actual diffusion very well.[15]

<< Figure 2 about here >>

In the following, we thus use the extent of the fixed-line voice-telephony network in a country in 1996 as a source of exogenous variation in the country's probability of having broadband Internet access. Since PIAAC measures ICT skills in 2011/2012, we argue that individuals living in countries with a farther-reaching voice-telephony network in 1996 were more likely to have early access to the Internet, increasing the chance and length of developing ICT skills through learning-by-doing until 2011/2012. The first-stage equation of our IV strategy then reads:

$$ICT_{ic} = \gamma_0 + \gamma_1 T_c + \gamma_2 X_{ic} + \gamma_3 X_c + \vartheta_{ic} \tag{4}$$

The main worry concerning this identification strategy is that pre-existing fixed-line networks directly affect wages today, which would violate the exclusion restriction. To dispel this concern, we condition our IV estimations on a set of country-level control variables that account for cross-country differences before broadband roll-out. First, we control for GDP per capita in 1996. This variable captures any direct positive economic effect of the fixed-line voice-telephony network (Röller and Waverman, 2001). Including this variable also controls for the fact that richer countries had a better-developed fixed-line infrastructure prior to broadband roll-out and pay higher wages

[14] The International Telecommunications Union (ITU) is the United Nations' agency for telecommunications.

[15] A very noticeable difference between actual and predicted broadband penetration appears for Korea. The Korean government heavily subsidized the roll out of fibre-to-the-home, resulting in a high actual broadband penetration that cannot be captured by the pre-existing fixed-line network.

today. Second, it is cheaper to roll out a fixed-line voice-telephony network in a country in which the population is spatially concentrated – which might also affect economic performance through agglomeration economies. Therefore, we further control for the share of the population living in rural areas in 1996.[16]

Another concern is that the instrument is just spuriously correlated with country-level variables that also affect ICT skills (such as labor-market institutions or quality of the education system). Therefore, Section 4 provides a careful analysis showing that the instrument influences different groups of people within the same country differently, and it does so in a way that is consistent with a learning-by-doing channel.

Finally, given that the instrument exclusively relies on between-country variation, we cluster standard errors at the country level (Moulton, 1986). Moreover, our analyses employ sample weights (provided in the PIAAC data) throughout. To account for cross-country differences in sample size in PIAAC, we restrict the sum of all individual-level weights within a country to be equal to one in the cross-country analysis.

4. Returns to ICT Skills

4.1 First-stage results

Before proceeding to the estimation of the returns to ICT skills, we take a closer look at the first stage of our instrumental-variable regressions, showing the effect of country-level fixed-line diffusion in 1996 on standardized individual-level ICT skills.

It is paramount for the validity of our identification strategy that the instrument explains ICT skills only of the part of the country population that can potentially be affected by it. Otherwise, the instrument may just be spuriously correlated with ICT skills. Our instrument basically reflects the technical availability of broadband Internet in a country in the first decade of the 2000s. Thus, it should only affect individuals who were most likely to use the Internet conditional on country-specific availability during this decade.

[16] Data on GDP per capita are provided by the OECD, data on the rural share are provided by the World Bank.

As a first check, we compare the first-stage relationship between natives, second-generation immigrants, and first-generation immigrants. While the first two groups are most likely to have lived in the PIAAC test country during the first decade of the 2000s, this is all but certain for the latter group. We thus expect to find a positive first-stage relationship for the first two groups, while the relationship should be considerably weaker for first-generation immigrants. Table 1 shows the expected positive first-stage relationship for natives and second-generation immigrants, both significant at the 1 percent level.[17] For first-generation immigrants, however, fixed-line diffusion and ICT skills are even negatively related.[18] Interestingly, the association with ICT skills of all other control variables is very similar across the three groups, indicating that the accumulation of ICT skills generally follows similar patterns for natives and both migrant types. Consequently, we do not consider first-generation immigrants in the subsequent analyses.

<< Table 1 about here >>

We also expect that our first-stage relationship should be strongest for individuals in an age group in which they were old enough to use the Internet in the first decade of the 2000s, but still young enough to be open to this new technology. Figure 3 shows the first-stage relationship for various age groups. The figure indeed reveals that fixed-line networks in 1996 influence ICT skills especially of persons between 20 and 49 years of age. Although there is some variation, ICT skills of persons in this age range are almost equally affected by the pre-existing fixed-line networks. However, we observe a strong decline in the effect of our instrument for age groups beyond age 49 and for the very young age group consisting of individuals aged 16-19. These results provide a rationale for restricting our main estimation sample to 20-49 year olds.[19]

[17] We only report specifications with all control variables included. See below for models where we include control variables successively.

[18] This negative association is hard to interpret because first-generation immigrants accumulated their ICT skills in a different country. A possible explanation for this result would be that first-generation immigrants with low ICT skills are more likely to migrate to countries with a highly-developed broadband infrastructure (resulting from the initial fixed-line networks).

[19] We also performed estimations for other age groups (35-54, 35-65, 16-65), yielding qualitatively similar results to those reported here.

<< Figure 3 about here >>

Since our instrument relies on between-country variation, our first-stage relationship may be driven by some country outliers. This would also question the external validity of our results. Figure 4 shows an added-variable plot for our first-stage regression with all control variables. To construct this graph, we have aggregated the residuals of the individual-level regressions to the country level, the level where the instrument varies. The figure reveals that the positive relationship between our instrument and ICT skills is evident across the entire sample.

<< Figure 4 about here >>

4.2 IV and OLS estimates

We will now turn to our detailed IV results, reported in Table 2.[20] As outlined above, we restrict our sample to natives and second-generation immigrants between 20 and 49 years of age. The table also reports the first-stage coefficient on pre-existing fixed-line diffusion and the *F*-statistic on the excluded instrument. In line with the evidence presented in Section 4.1, the instrument is a strong predictor of ICT skills. In the most demanding specification with all control variables (Column 5), the *F*-statistic is 30.7 and thus well above the threshold for a strong instrument. The coefficient estimate suggests that increasing the voice telephony penetration rate from 0 to 100 percent is associated with an increase in ICT skills of about 8.1 country-level standard deviations (66 points). While this effect appears to be very large, one should note that the diffusion of fixed-line networks in 1996 effectively varies only between 17 percent (Poland) and 68 percent (Sweden).[21] Our first-stage estimate thus suggests that an increase in the diffusion of fixed-line networks from the

[20] All results are robust to using country-level aggregates of ICT skills instead of individual-level skills. We also experimented with aggregating all variables in the model to the country level, and found the results to be robust. OLS results of cross-country regressions (with and without control variables) are plotted in Figure A-2 in the appendix.

[21] See Table A-2.

minimum to the maximum value in the sample is associated with an increase in ICT skills of 34 points.[22]

The second stage shows the effect of an increase in ICT skills induced by pre-existing fixed-line networks on wages. We start out by showing the unconditional correlation and then stepwise add further country-level and individual-level control variables. We observe that controlling for some basic characteristics of a country prior to the first emergence of broadband significantly reduces the coefficient on ICT skills, while this is not the case when adding individual-level controls. We find the largest decrease in the ICT-skill coefficient when including GDP per capita in 1996, which suggests that the extent of the voice telephony networks in 1996 is correlated with a country's stage of economic development (Column 2). Results hardly change when we further control for the share of the population living in rural areas in 1996 (Column 3).[23] Likewise, the coefficient on ICT skills remains very similar when we include controls for individual characteristics (i.e., quadratic polynomial in work experience, gender, and children) in Column 4, and get only slightly smaller when we additionally control for years of schooling (Column 5).

<< Table 2 about here >>

In terms of magnitude, the ICT-skill coefficient of 0.171 (Column 5) implies that a one-standard-deviation increase in individual-level ICT skills attributable to a historically larger fixed-line network leads to a 17.1 percent increase in individual wages. This effect is significantly larger than the effect in an analogous OLS regression (Column 5 of Table 3). The OLS estimate suggests that a one-standard-deviation increase in individual-level ICT skills only leads to a 6.6 percent increase in individual wages.[24] The difference in effect sizes may be due to classical measurement error in the

[22] Table A-3 reports all first-stage coefficients for the corresponding specifications in Table 2. While the country-level variables (GDP per capita and share of the rural population, both measured in 1996) and work experience are not associated with ICT skills, we observe that, on average, women have lower ICT skills than men and parents have lower ICT skills than persons without children. Not surprisingly, the number of years of schooling is positively associated with ICT skills.

[23] Beyond these two basic country characteristics, we will account for further country-level controls in the Section 4.5.

[24] A comparable effect is found in a regression with country fixed effects (see Column 6 of Table 3). This specification is however not feasible in our IV estimation.

ICT-skill variable leading to a bias of the OLS coefficient towards zero (see Hanushek, Schwerdt, Wiederhold, and Woessmann, 2015, for a discussion).

Another explanation for the difference in effect sizes between IV and OLS might be that the OLS results not just reflect the wage effect of ICT skills but also the effect of other types of skills.[25] Our instrument, however, isolates the effect of ICT skills on wages (see also Section 4.3). A significantly higher IV coefficient as compared to the OLS coefficient suggests that returns to ICT skills are higher than returns to other skills, which would be consistent with ICT skills being especially important in modern knowledge-based economies. Corroborating this explanation, the IV coefficient on ICT skills hardly changes when we add years of schooling as a further control variable, while in the corresponding OLS estimation the ICT-skill coefficient reduces to nearly half its size. This also suggests that the exposure to ICT infrastructure induced by the size of the initial fixed-line network systematically captures variation in the ICT skills that is unrelated to an individual's general human capital endowment.[26]

<< Table 3 about here >>

4.3 Placebo tests

In order to be able to interpret the above IV results as showing a causal effect of ICT skills on wages, we have to be sure that the spread of the voice-telephony networks that existed before the emergence of broadband Internet insulates the effect of ICT skills on wages from that of other skills. We thus replace ICT skills in our first-stage regression with numeracy and literacy skills, respectively, which are also available in the rich PIAAC dataset. If our instrument indeed isolates the effect of ICT skills, it should be irrelevant in explaining numeracy and literacy skills. Table 4 shows

[25] Recall from Section 2 that ICT skills are highly correlated with both literacy and numeracy skills.

[26] Using a sample of prime-age, full-time employed workers in PIAAC, Hanushek, Schwerdt, Wiederhold, and Woessmann (2015) find in OLS regressions that ICT skills are systematically less related to individual wages than literacy and numeracy skills. When estimating a specification analogous to theirs (Table 3, Column 6 without controlling for the presence of children and years of schooling), we also find that the returns to ICT skills (11.9 percent) are smaller than those to numeracy (16.0 percent) and literacy (14.9 percent) skills. However, it is hard to interpret these results as evidence showing that ICT skills are less valued on the labor market than the more traditional skills because the OLS estimates are obviously confounded by reverse causality and omitted variables. It may also be that ICT skills as measured in PIAAC capture skills relevant on the labor market less well than measured literacy and numeracy skills, leading to a larger attenuation bias. Our IV approach solves these problems.

the results of these placebo tests. Controlling for ICT skills, we find that neither numeracy nor literacy skills are significantly related to the pre-existing fixed-line network (Columns 1 and 2). We consider this as strong evidence that our instrument captures the "right" type of variation because ICT skills and numeracy/literacy skills are highly correlated at the individual level. Another way to check whether our instrument is orthogonal to literacy and numeracy skills is to control for these skills in the first-stage regression with ICT skills as outcome. As Columns 3 and 4 reveal, controlling for other skill domains hardly changes the coefficient of our instrument.[27]

<< Table 4 about here >>

4.4. Where are ICT skills learned?

Next, we provide further evidence for the validity of our identification strategy by exploring where ICT skills are learned. The basic idea behind our instrument is that early and more wide-spread availability of access to the Internet via DSL technology increases ICT skills through learning-by-doing. DSL is one of the most frequent fixed-line access technologies to the Internet. This is true for private subscribers as well as subscriptions of small and medium enterprises (SMEs). Only large firms have access to the Internet via leased lines and are typically not constrained by the non-availability of DSL. Consequently, our instrument does not discriminate between whether ICT skills are learned at home or at work. The rich PIACC dataset provides information on the frequency of Internet use either at home or at work. We can thus split the sample by Internet use intensity at home and at work and separately estimate the first-stage regressions for these subgroups. The results of this exercise are shown in Table 5. The results in Panel A indicate that Internet use at home and at work are important means to acquire ICT skills. We find positive first-stage effects for the groups of individuals who often use the Internet in their everyday lives (i.e., at home, at work, or both at home and at work). Persons who are not frequently using the Internet at home and at work are not affected by the instrument, which suggests the existence of a learning-by-doing channel.

PIACC does not only provide information on Internet use intensity but also on computer use intensity. Since computer use is not constrained by the availability of Internet access, we would

[27] It is important to note that we refrain from controlling for numeracy or literacy skills in the 2SLS regressions because such approach would essentially isolate the variation that is common to ICT skills and numeracy/literacy. This is precisely the variation we do not want our instrument to capture.

expect that the first-stage relationship is not affected by the frequency of computer use. Panel B, which restricts the sample to persons who are not frequently using the computer in their everyday lives, shows that this is indeed the case.

<< Table 5 about here >>

Another way to show that the channel through which our instrument affects ICT skills is Internet use (and not computer use) is to replicate Table 5 with computer use. Results are shown in Table 6. Splitting the sample by computer use intensity at home and at work does not affect the first-stage estimation; in fact, we do not observe any insignificant first-stage relationship in this tabulation (Panel A).[28] However, once we constrain the sample to persons who only infrequently use the Internet, the first-stage relationships become insignificant for all types of computer use (Panel B), indicating that the variation in the instrument stems from internet use, not from computer use.

<< Table 6 about here >>

4.5. Robustness

In Tables 7 and 8, we present a series of robustness checks designed to test the sensitivity of our main results to adding further controls and to changes in the estimation sample. In our baseline specification, we have controlled only for two country-level variables, that is, GDP per capita in 1996 and the share of the rural population in 1996. One might argue that fixed-line diffusion in 1996 might be correlated with other country-level variables that also affect a country's wage level. Given that variation in our IV specification comes from differences in the fixed-line diffusion across 19 countries, degrees of freedom for adding further country-level controls are somewhat limited. We therefore include further country-level controls one-by-one. These control variables include the GDP share of the service sector, union density, employment protection legislation, public sector share, youth unemployment rate, share of persons currently enrolled in tertiary education, as well as

[28] Note that these specifications can also be regarded as an additional placebo test.

TV cable diffusion[29] and cellphone diffusion to proxy for Internet-access technologies other than DSL.[30] Control variables characterizing the labor market, the industry structure, as well as the demographic structure in a country are meant to capture factors that might influence both a country's wage level and its general dependence on ICT. The results, shown in Columns 1 to 8 of Table 7, demonstrate that the estimated returns to ICT skills remain very similar when including further country-level controls.

Another potential concern is that our effects are driven by those countries that have both comparatively low broadband diffusion and comparatively low wages. Closer inspection of the data revealed that the three post-communist countries in our sample (the Czech Republic, Poland and the Slovak Republic) had the lowest fixed-line diffusion in 1996 and also paid lowest wages in 2012 (see Tables A-1 and A-2). It is therefore reassuring that the coefficient on ICT skills remains significant at the 5 percent level when dropping the post-communist countries from the sample (Column 9). Still, returns to ICT skills decrease by about one half in this restricted country sample.[31]

<< Table 7 about here >>

In Table 8, we assess the robustness of our baseline results to including additional individual-level control variables in the model. First, it may be argued that actual work experience is endogenous to skill levels because people may use and reinforce skills at the job. Actual work experience may thus capture a channel of the effect of skills on wages. Therefore, in Columns 1 and

[29] The pre-existing TV-cable network has been upgraded for broadband Internet use in many countries (Czernich, Falck, Kretschmer, and Woessmann, 2011).

[30] Data on union density and employment protection legislation are provided by the OECD and refer to 2011 unless otherwise noted. Union density refers to 2009 in the Czech Republic and to 2010 in Denmark, Estonia, and Poland. The employment-protection indicator is the weighted sum of sub-indicators concerning the regulations for individual dismissals (weight of 5/7) and additional provisions for collective dismissals (2/7), incorporating 13 data items (see Venn, 2009, for details). Data on TV cable diffusion in 1996 are taken from ITU. All remaining variables refer to 2012. Service sector shares are provided by the World Bank and Statistics Canada. The share of persons enrolled in tertiary education is provided by the UNESCO Institute for Statistics. For Canada, we constructed the share of persons enrolled in tertiary education by dividing the total number currently in tertiary education (taken from Statistics Canada) by population size (taken from the OECD). The youth unemployment rate is provided by the OECD. The public-sector share is calculated from the PIAAC data.

[31] Results are also robust to specifications that include continental fixed effects or restrict the analysis to European countries only.

2 we replace actual work experience by age and potential work experience (age minus years of schooling minus six), respectively. Likewise, full-time jobs may be more likely to sustain skill levels by more regularly practicing skills or by providing the money to invest in professional development and adult education. Thus, whether or not a person is full-time employed may be an important omitted variable in the baseline specification. In Column 3, we control for a full-time employment indicator.[32] Further, if family background is related to skill development and family ties help people find a better job, the association between skills and wages will be confounded. Column 4 captures the influence of parental background by controlling for parental education. Similarly, a person's health condition may positively affect both skill acquisition and wages. Column 5 thus controls for a measure of self-assessed health status available in PIAAC. Finally, we add controls for 10 one-digit occupation (ISCO) categories (Column 6) and 21 one-digit industry (ISIC) categories (Column 7), which account for differences in wages across occupations and industries. Neither of these additional control variables qualitatively changes the baseline results.

<< Table 8 about here >>

Taken together, the evidence provided in Tables 7 and 8 strongly suggests that our instrumental-variables estimation strategy did indeed identify variation in ICT skills that is independent of potentially omitted variables at the level of countries or individuals.

Finally, it is important to note that our 2SLS approach is basically a reduced-form analysis of the following line of argumentation: (1) fixed-line-diffusion in 1996 predicts broadband Internet diffusion in 2012; (2) broadband Internet diffusion predicts ICT skills; and (3) ICT skills predict wages. To provide evidence for this mechanism, we estimate a recursive system of three equations using a seemingly unrelated regressions model. Results shown in Table A-4 imply that past fixed line diffusion is positively associated with the availability of broadband Internet today (first equation). In the second equation, we find that Internet diffusion is positively related to ICT skills, which in turn

[32] Full-time employment is defined as working at least 30 hours per week. In Australia and Austria, the full-time working status is based on a question of whether a respondent works full-time. Since the Canadian data neither report working hours nor work status, we were unable to create an indicator for full-time employment in the Canadian sample.

significantly predict wages in the third equation. Strikingly, estimated returns to ICT skills in these models are very similar to the 2SLS estimation results in Table 2.[33]

5. Within-Country Evidence

Thus far, we provided evidence on the wage returns to ICT skills from a cross-country IV model. We now zoom into a single country, Germany, which allows us to exploit peculiarities in the structure of the pre-existing voice-telephony network as a source of plausibly exogenous variation in ICT skills. In West Germany, the general structure of the voice-telephony network dates back to the 1960s when the provision of telephone services was a state monopoly with the declared goal of providing universal telephone service to all German households. In traditional telephone networks, the length of the so called last mile, that is a pair of copper wires reaching from every household to the main distribution frame (MDF), is irrelevant for the quality of voice-telephony services. In contrast, in a DSL network, which is the dominant broadband technology in Germany, the last-mile distance does play a crucial role, because the maximum bandwidth depends on the length of the copper wire between the household and the MDF.[34] When surpassing a threshold of about 4,200 meters (2.6 miles), DSL technology is no longer feasible and parts of the copper wire (typically placed between the MDF and street cabinet) must be replaced with fiber wire in order to provide DSL. This, however, involves costly earthworks that increase with the length of the bypass.[35]

We follow Falck, Gold, and Heblich (2014) in using the 4,200-meter threshold as a source of exogenous variation in the availability of DSL technology in a municipality. Each household is assigned to exactly one MDF.[36] We calculate the distance of a municipality's geographic centroid (as a proxy for the average distance of a household to the next MDF) and merge this information, as

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[33] In unreported analysis, we also explore whether the impact of ICT skills differs across various worker subgroups. We perform subsample estimations by gender and education level, and also estimate effects separately for private-sector and public-sector employees, and for workers in manufacturing and services. The sample splits reveal that returns to ICT skills are quite homogenous across the considered subgroups. Results are available on request.

[34] Figure A-3 shows the structure of a DSL network based on the traditional voice-telephony network.

[35] The costs of rolling-out one kilometer of fiber wire sub-surface amount to 80,000 euro, with an additional 10,000 euro to install a new node where the remaining part of the copper wires is connected to the fiber wire (Falck, Gold, and Heblich, 2014).

[36] Information on the exact location of the MDFs was kindly provided by Deutsche Telekom AG.

well as information on the technological availability of DSL[37], with the German PIAAC data.[38] Following a similar line of argumentation as in the cross-country identification strategy, we expect that PIAAC respondents in municipalities above the 4,200-meter threshold have lower ICT skills because they had less opportunity to accumulate ICT skills due to lacking high-speed Internet access.

In an extension, we even narrow down the sample further and focus on municipalities without an own MDF. While densely populated municipalities always have at least one own MDF and are typically below the 4,200-meter threshold, less agglomerated municipalities often share an MDF. The choice of MDF locations in these less-agglomerated areas was determined by such restrictions as the availability of lots and buildings to host an MDF at the time when the structure of the voice-telephony network was planned, i.e., in the 1960s. The sample thus includes only municipalities that were not chosen for hosting an MDF, which homogenizes the sample of municipalities with respect to their socioeconomic characteristics. Some municipalities, however, were (arguably randomly) lucky to be close enough to an MDF in another municipality to be able to access broadband Internet. This provides variation in the instrument in the restricted sample.[39]

In Table 9, we present results from IV regressions using as instrument a dummy variable that equals one for municipalities with distances above the threshold of 4,200 meters (Columns 1--3). Since the instrument is measured at the municipality level, we cluster standard errors by municipality. We further account for the municipality's economic situation and its age composition by adding the unemployment rate and the population share of individuals above 65 years[40], respectively, as control variables. At the individual level, we control for a quadratic polynomial in work experience, gender,

[37] Availability of DSL is measured as the percentage of households in a municipality for which DSL is technologically feasible. Data are taken from the German Broadband Atlas commissioned by the German Federal Ministry of Economics.

[38] We thank Anja Perry at GESIS Germany for making the municipality-of-residence information in the PIAAC data available to us.

[39] We impose the following sample restrictions throughout specifications in the within-country analysis: First, we exclude East German municipalities since we cannot rule out that location decisions for the MDFs in East Germany, which were made after the reunification in the 1990s, were partly determined by unobserved characteristics of the municipalities that are also correlated with individual wages. Second, we drop Berlin from our analysis because we are unable to distinguish between former West and East Berlin in terms of DSL availability. We also maintain the sample restrictions from the cross-country analysis, i.e., we include only employees aged 20-49 and drop first-generation migrants.

[40] Data come from the German Federal Statistical Office.

and presence of children.[41] In the full sample (Panel A), the first-stage results show that persons in municipalities above the 4,200-meter threshold have substantially lower ICT skills, which is in accordance with the proposed learning-by-doing channel. In the specification with all controls, we find that persons in municipalities with a distant MDF have 63 percent of a standard deviation lower ICT skills than persons in municipalities with a close MDF. Although the threshold instrument has a sizable effect on individual ICT skills, point estimates are rather imprecise. A major reason for the low instrument strength is that people are mobile between municipalities. We, however, observe their municipality of residence only at the time of the PIAAC survey in 2011/2012.[42] To address a potential weak-instrument problem (e.g., Bound, Jaeger, and, Baker 1995), we use LIML to obtain our IV estimates since LIML minimizes the coefficient estimate bias associated with weak instruments.[43]

Turning to the second stage of our IV estimation in the upper part of Panel A of Table 9, we find significantly positive returns to ICT skills: a one-standard-deviation increase in ICT skills attributable to the technical threshold in the municipalities' distance to the MDF increases wages by 25 percent in the full-control model (Column 3). This estimate is somewhat larger than the corresponding estimate in the cross-country sample of 19.4 percent (see Column 4 of Table 2).[44] The larger returns in Germany are consistent with the results in Hanushek, Schwerdt, Wiederhold, and Woessmann (2015) showing that Germany is one of the countries with the highest returns to cognitive skills worldwide. In line with the cross-country analysis, the OLS estimates in Columns (4)--(6) are lower in magnitude than the corresponding IV estimates.

In Panel B, we use the threshold instrument in a sample of less-agglomerated West German municipalities without an own MDF. The size of this restricted sample is considerably smaller than that of the full sample because the sampling of municipalities in PIAAC was proportional to municipality size (Rammstedt, 2013). However, the magnitude of the threshold estimate even

[41] ICT skills in the within-country IV analysis are standardized using the municipality-level standard deviation because the instrument relies only on variation across municipalities.

[42] While we cannot pin down the exact mobility rate at the level of municipalities, estimations based on the German *Mikrozensus* show that on average 3 percent of the population moves to a different district each year.

[43] We also construct the Anderson and Rubin (AR) 95% confidence intervals, which are robust to weak instruments (Anderson and Rubin, 1949). The AR confidence intervals are quite similar to those obtained in the IV estimates and never include zero. This suggests that our estimates do not suffer from a weak-instrument problem biasing the IV results in a meaningful way. Results are available on request.

[44] When we additionally account for years of schooling, ICT skills remain statistically significant (coef. = 0.200, s.e. = 0.115), with an F-statistic of the excluded instrument of 3.7.

increases in this more homogenous sample, while the second-stage results remain very similar to the full-sample results. Although we have very limited degrees of statistical freedom in the reduced sample due to the clustering of standard errors at the municipality level, returns to ICT skills are almost as precisely estimated as in the full sample.

<< Table 9 about here >>

The three-equation estimations in Table A-5 indicate that the reduced-form first-stage estimates in Table 9 indeed capture the effect of Internet availability on ICT skills. We find that municipalities above the 4,200-meter threshold have on average a 5 to 7 percentage points lower broadband availability, while broadband availability positively affects individual ICT skills. Reassuringly, wage returns in the three-equation estimations are very similar to those obtained in the IV models. Further support for the idea that our first-stage results can be explained by a learning-by-doing channel in the development of ICT skills is provided by descriptive evidence from the PIAAC background questionnaire, showing that respondents living in municipalities above the threshold use the Internet less often at home.[45] We do not find discernible differences between people above and below the threshold for internet use at work and for computer use either at home or at work.

Finally, to ensure that our within-country identification strategy insulates the effect of ICT skills on wages from the effect of general ability, Table 10 presents Placebo tests analogous to those in Table 4 for the cross-country sample. While neither numeracy nor literacy skills are systematically affected by the threshold instrument and even show *positive* coefficients throughout specifications, ICT skills are consistently negatively affected by the instrument even conditional on the other skill domains.

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[45] The share of people who report that they use the Internet at home often is only 46 percent in the above-threshold sample (61 percent in the below-threshold sample). A person uses the internet "often" when she reports in the PIAAC background questionnaire that she uses the internet for at least one of the following activities every day: writing or reading e-mails, searching for various issues, conduct transactions. We apply the same definition for the results presented in Table 5.

<< Table 10 about here >>

6. Conclusion

This paper provides the first evidence on the returns to ICT skills on the labor market, using a novel dataset that measures individuals' ICT skills in 19 developed countries. We identify exogenous variation in ICT skills exploiting the extent of the traditional voice telephony networks, which were upgraded for fast Internet use. The underlying idea is that ICT skills are developed through learning-by-doing for which Internet availability is a precondition. The instrument is a strong predictor of ICT skills, and a series of validity tests provide support for the existence of the learning-by-doing channel. Estimations additionally control for a rich set of individual-level and country-level variables, including a person's acquired level of schooling and general economic conditions before widespread broadband roll-out.

Our results indicate that higher ICT skills are systematically related to higher wages. In the cross-country analysis, we find that a one-standard-deviation increase in ICT skills leads to an increase in wages of 17.1 percent. Estimates from analogous OLS specifications are substantially lower, with returns to skills of 6.6 percent. A possible interpretation for this difference is that the OLS results rather capture a general skill effect, given that ICT skills as measured in PIAAC are highly correlated with the other skill domains included in PIAAC, numeracy and literacy (and presumably also with further, unobserved skills). The IV approach, however, is able to insulate the wage effect of ICT skills from that of other types of skills. This interpretation is supported by a Placebo test, showing that pre-existing fixed line networks cannot explain any variation in numeracy and literacy. Returns to ICT skills are also sizable when we use a different source of identifying variation by exploiting technological peculiarities of the pre-existing voice telephony network in Germany that effectively excluded many municipalities from accessing high-speed Internet.

By showing that ICT skills are quite substantially rewarded on the labor market, our results provide support for Neelie Kroes' notion of ICT skills as "the new literacy." Still, we want to caution the reader against interpreting our findings as conclusive evidence that ICT skills are valued higher than any other type of skills in modern knowledge-based economies. Providing such evidence would require to identify sources of variation that systematically capture other domain-specific skills, which are not confounded by a person's general ability. However, given that evidence on the causal returns to cognitive skills (general or domain-specific) has been extremely scarce thus far, we consider our work as a suitable starting point to further inquire causality in the returns-to-skills estimation.

Our research is also relevant for the recent discussion revolving around e-learning, that is, the use of ICT-based teaching methods as well as virtual learning technologies in the classroom and at home. The existing literature on the effects of ICT on student achievement mostly suggests overall zero or very weak effects (for an overview, see Bulman and Fairlie, 2015) with only positive effects of some types of uses (Falck, Mang and Woessmann, 2015). However, there is evidence that e-learning indeed helps developing ICT-related skills (Malamud and Pop-Eleches, 2011). Our results suggest that building ICT skills through e-learning, even if e-learning itself is not positively associated with school grades, might prove beneficial for students' future labor-market outcomes.

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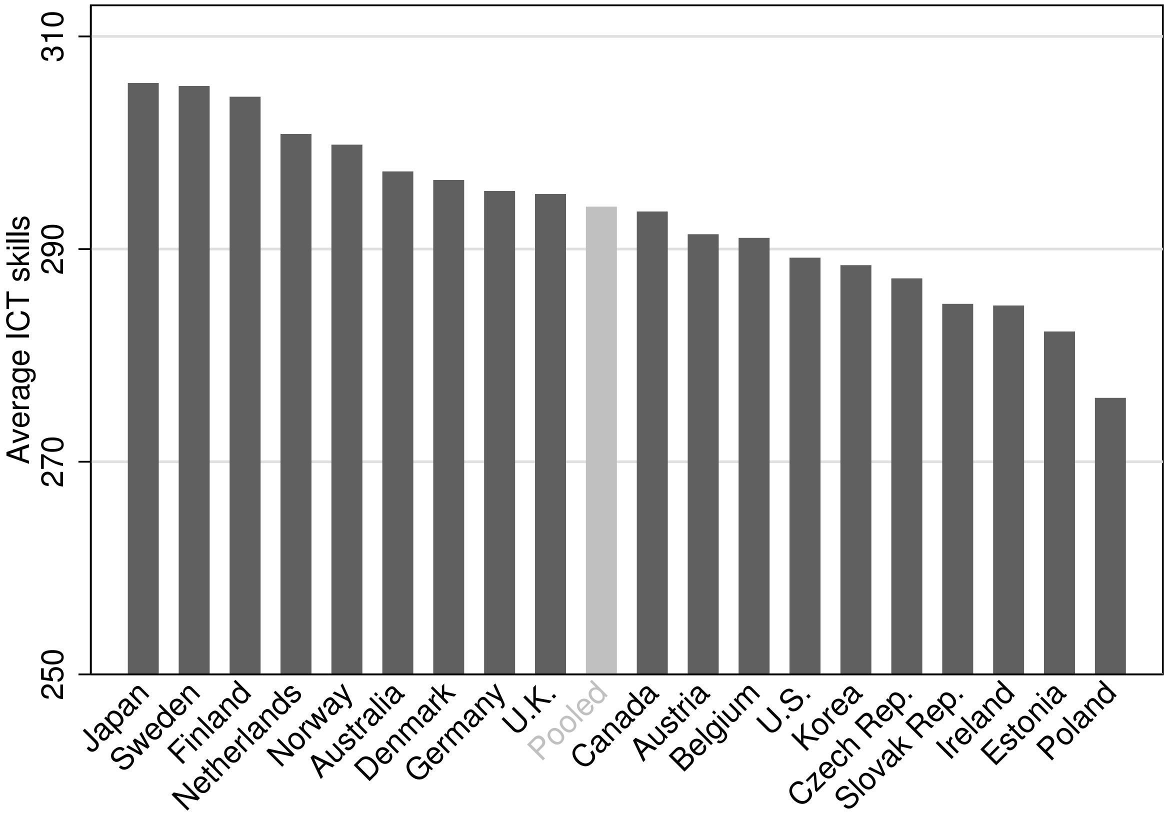
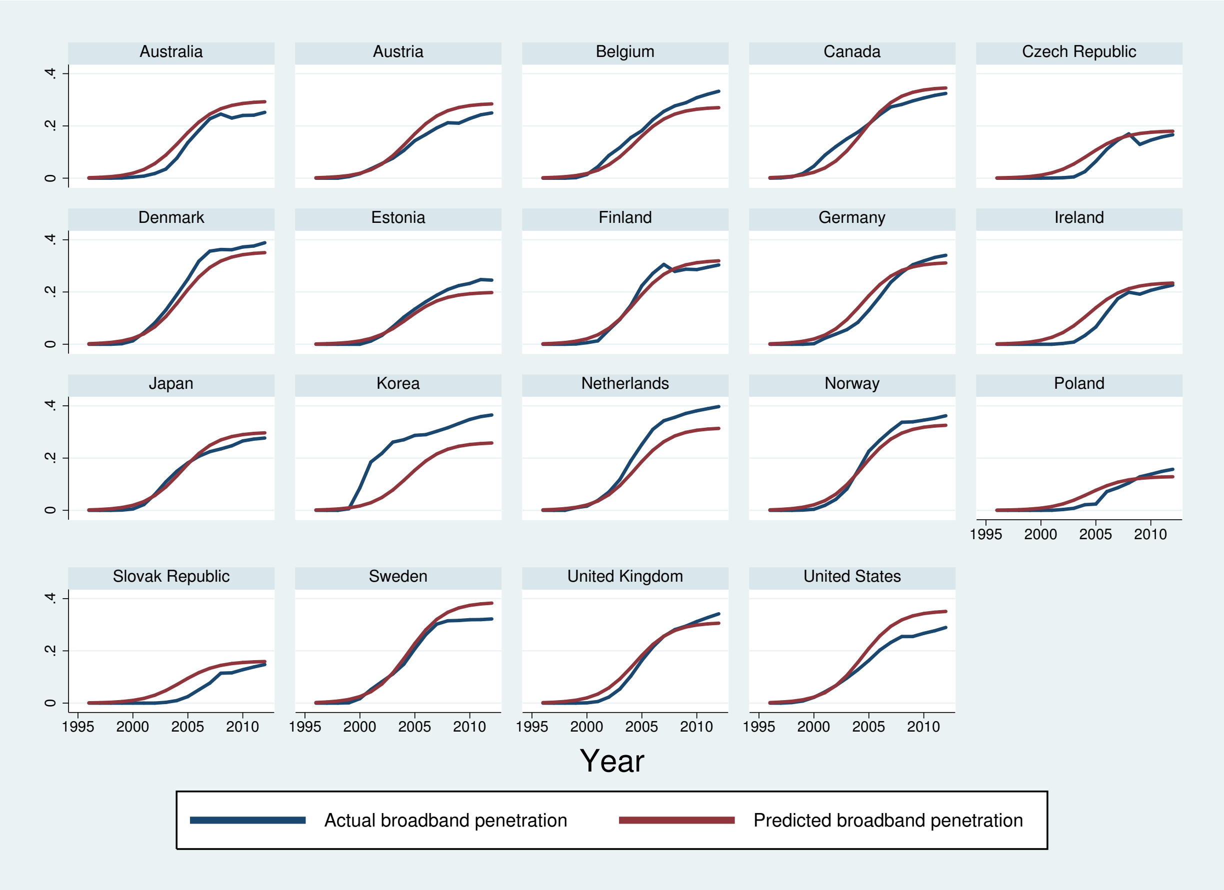
Figures and Tables

Figure 1: ICT Skills around the World



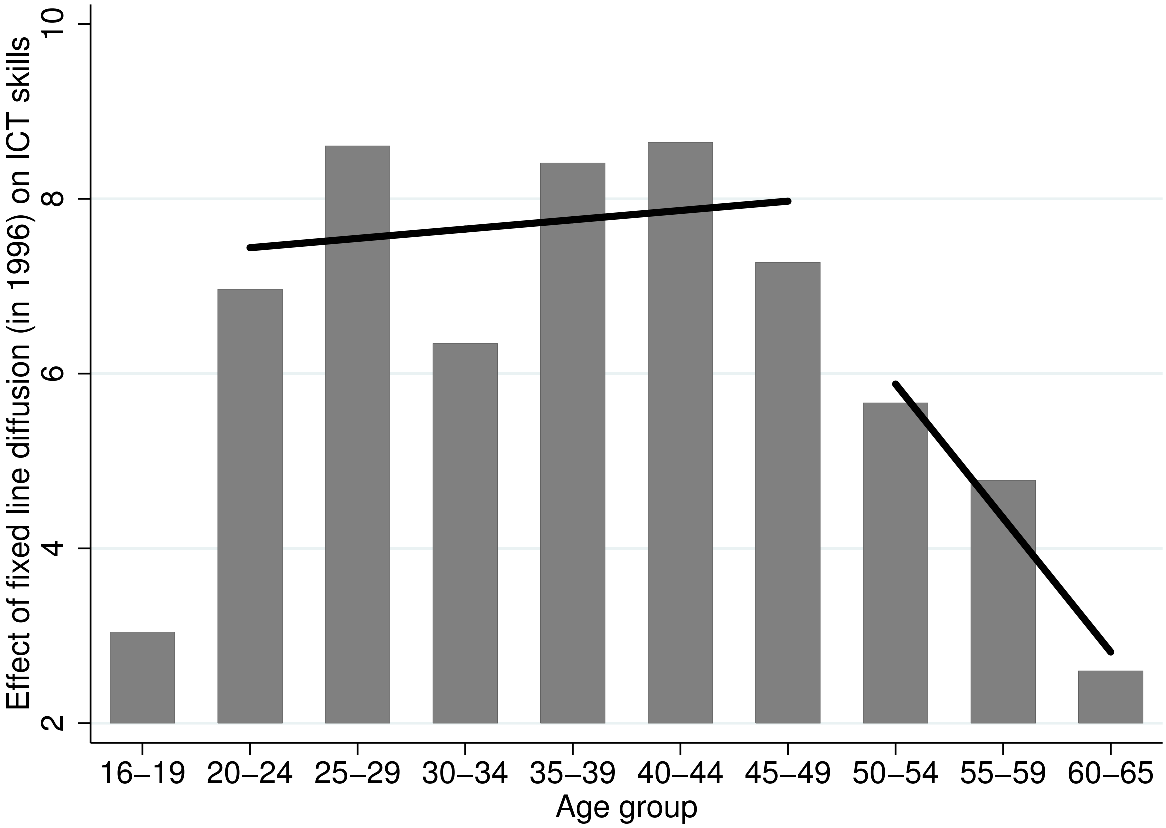
Notes: Average ICT skills across countries. Sample: employees aged 20–49 (no first-generation migrants). *Data source:* PIAAC.

Figure 2: Broadband Diffusion across Countries: Actual and Predicted Curves, 1996–2012



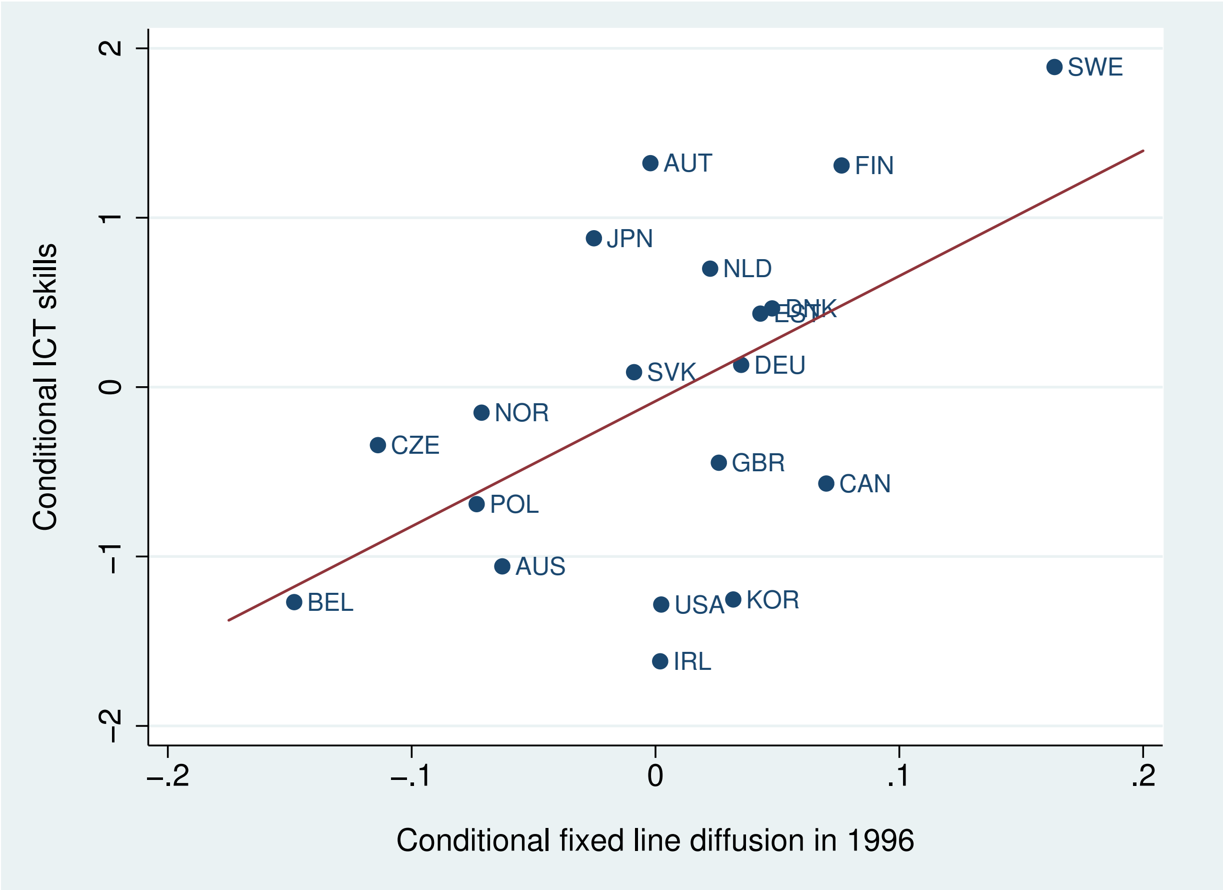
Notes: Predicted broadband diffusion is derived from nonlinear least squares estimation of a diffusion curve based on telephone access lines per 100 inhabitants in 1996. See Section 3 for details. *Data source:* ITU.

Figure 3: Past Fixed Line Diffusion and ICT Skills by Age Group



Notes: Coefficient estimates on fixed line diffusion (in 1996) for indicated 5-year age groups in a regression of ICT skills (standardized to std. dev. 1 across countries) on fixed line diffusion and all control variables included in Table 2, Column (5). Sample: employees, no first-generation migrants. Slopes of solid lines reflect average change in the effect of fixed line diffusion on ICT skills by age groups (separately estimated for ages 20-49 and 50-65). *Data sources:* ITU, OECD, PIAAC.

Figure 4: Past Fixed Line Diffusion and ICT Skills (First Stage)



Notes: Added-variable plot from a regression of ICT skills on fixed line diffusion (in 1996) and all control variables included in Table 1, Column (5). Sample: employees aged 20–49, no first-generation migrants. Based on individual-level regressions that are then aggregated to the country level. Solid line is fitted through all country-level observations. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 1: Past Fixed Line Diffusion and ICT Skills by Migration Status

ICT skills	Natives	2nd-gen. migrants	1st-gen. migrants
Fixed line diffusion in 1996	8.090***	8.544***	–3.268**
	(1.442)	(1.584)	(1.325)
GDP per capita in 1996 (/1000)	–0.039	–0.045	–0.026
	(0.029)	(0.030)	(0.022)
Rural population in 1996	–2.475	–0.226	–3.416
	(1.977)	(1.361)	(2.242)
Experience	–0.017	–0.006	0.049
	(0.028)	(0.043)	(0.053)
Experience^2 (/100)	–0.213**	–0.106	–0.149
	(0.078)	(0.129)	(0.137)
Female	–0.886***	–0.628***	–0.792***
	(0.110)	(0.163)	(0.204)
Children	–0.760***	–0.894***	–1.763***
	(0.120)	(0.122)	(0.188)
Years of schooling	0.648***	0.685***	0.658***
	(0.045)	(0.032)	(0.057)
R squared (adjusted)	0.18	0.18	0.16
Individuals	36,667	4,014	4,842
Countries	19	19	19

Notes: Ordinary least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49. ICT skills are standardized to std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Native:* participant and both parents born in the country of residence. *1st-gen. migrants:* participant born abroad; at least one parent as well. *2nd-gen. migrants:* mother, father, or both born abroad; participant born in country of residence. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Rural population in 1996:* share of total population living in rural areas in 1996. *Children:* 1 = respondent has at least one child; 0 = otherwise. GDP per capita is measured in PPP-US-$. Fixed line diffusion, GDP per capita, and rural population share are measured at the country level; all other variables are measured at the individual level. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 2: Returns to ICT Skills: Instrumental-Variables Estimates

Second stage (Dependent variable: log gross hourly wage)					
	(1)	(2)	(3)	(4)	(5)
ICT skills	0.362***	0.201**	0.199*	0.194**	0.171**
	(0.083)	(0.089)	(0.106)	(0.097)	(0.067)
GDP per capita in 1996 (/1000)		0.020***	0.020***	0.015**	0.018***
		(0.006)	(0.006)	(0.007)	(0.005)
Rural population in 1996			–0.025	0.016	0.062
			(0.724)	(0.690)	(0.724)
Experience				0.031***	0.035***
				(0.007)	(0.005)
Experience^2 (/100)				–0.000	–0.022
				(0.044)	(0.020)
Female				–0.019	–0.020
				(0.061)	(0.057)
Children				0.196**	0.173***
				(0.090)	(0.062)
Years of schooling					–0.034
					(0.041)
First stage (Dependent variable: ICT skills)					
Fixed line diffusion in 1996	5.686***	5.765***	5.338***	5.552***	8.075***
	(0.840)	(1.276)	(1.384)	(1.226)	(1.456)
Instrument F statistic	45.8	20.4	14.9	20.5	30.7
Individuals	40,865	40,865	40,865	40,865	40,865
Countries	19	19	19	19	19

Notes: Two-stage least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Dependent variable in second stage, *log gross hourly wage*, is measured in purchasing power parities. ICT skills are standardized to std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. See Table A-3 for results of first-stage regression models. Fixed line diffusion, GDP per capita, and rural population share are measured at the country level; all other variables are measured at the individual level. See Table 1 for details on the variables. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 3: Returns to ICT Skills: Least Squares Estimates

Dependent variable: log gross hourly wage	(1)	(2)	(3)	(4)	(5)	(6)
ICT skills	0.132***	0.099***	0.096***	0.122***	0.066***	0.060***
	(0.019)	(0.011)	(0.011)	(0.010)	(0.011)	(0.007)
GDP per capita in 1996 (/1000)		0.033***	0.030***	0.027***	0.026***	
		(0.004)	(0.004)	(0.004)	(0.004)	
Rural population in 1996			–0.604	–0.561	–0.838**	
			(0.452)	(0.458)	(0.370)	
Experience				0.038***	0.032***	0.033***
				(0.004)	(0.003)	(0.003)
Experience^2 (/100)				–0.071***	–0.052***	–0.056***
				(0.010)	(0.008)	(0.006)
Female				–0.120***	–0.150***	–0.163***
				(0.020)	(0.019)	(0.019)
Children				0.050***	0.046***	0.047***
				(0.015)	(0.013)	(0.010)
Years of schooling					0.065***	0.066***
					(0.007)	(0.004)
Country fixed effects						Yes
R squared (adjusted)	0.05	0.27	0.28	0.38	0.45	0.53
Individuals	40,865	40,865	40,865	40,865	40,865	40,865
Countries	19	19	19	19	19	19

Notes: Ordinary least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Dependent variable is measured in purchasing power parities. ICT skills are standardized to std. dev. 1 across countries. GDP per capita and rural population share are measured at the country level; all other variables are measured at the individual level. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 4: Placebo Test

Dependent variable: cognitive skills in	Numeracy	Literacy	ICT	ICT
Fixed line diffusion in 1996	–0.378	0.682	4.472***	3.150***
	(1.450)	(1.063)	(1.155)	(1.018)
ICT skills	0.573***	0.636***		
	(0.016)	(0.016)		
Numeracy skills			0.848***	
			(0.016)	
Literacy skills				0.846***
				(0.013)
GDP per capita in 1996 (/1000)	–0.020	–0.028	–0.004	0.005
	(0.026)	(0.018)	(0.013)	(0.012)
Rural population in 1996	–1.627	–1.724**	0.211	0.409
	(2.011)	(0.798)	(1.355)	(0.880)
Experience	0.064***	0.046***	–0.063***	–0.047***
	(0.010)	(0.011)	(0.016)	(0.014)
Experience^2 (/100)	–0.087***	–0.089***	–0.028	–0.016
	(0.026)	(0.030)	(0.045)	(0.041)
Female	–0.823***	0.075	0.259***	–0.458***
	(0.079)	(0.062)	(0.083)	(0.081)
Children	0.358***	0.137**	–0.700***	–0.472***
	(0.076)	(0.064)	(0.079)	(0.062)
Years of schooling	0.233***	0.272***	0.138***	0.071***
	(0.025)	(0.020)	(0.015)	(0.020)
R squared (adjusted)	0.57	0.62	0.58	0.62
Individuals	40,865	40,865	40,865	40,865
Countries	19	19	19	19

Notes: Ordinary least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Numeracy, literacy, and ICT skills are standardized to std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. Fixed line diffusion, GDP per capita, and rural population share are measured at the country level; all other variables are measured at the individual level. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 5: Internet Use at Home and at Work

Panel A: Full Sample

	Internet use home: Often		Internet use home: < Often	
	Internet use work			
	Often	< Often	Often	< Often
Fixed line diffusion in 1996	6.770***	5.407**	6.492***	1.640
	(1.307)	(2.447)	(1.704)	(1.806)
Instrument F statistic (from 2SLS)	26.8	4.9	14.5	0.8
Individuals	18,597	4,355	6,720	3,258
Countries	19	19	19	19

Panel B: Low Computer-Use Sample

Fixed line diffusion in 1996	6.964***	5.993*	7.544***	1.712
	(1.605)	(3.189)	(1.884)	(1.738)
Instrument F statistic (from 2SLS)	18.8	3.5	16.0	1.0
Individuals	4,524	2,835	2,389	2,623
Countries	19	19	19	19
	Controls in Panels A + B			
Country characteristics	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes

Notes: Ordinary least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Panel A includes full sample, Panel B includes only workers how use computers at home and at work less than every day (see Table 6 for details). ICT skills are normalized with std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Internet use:* how often a person performs the following activities at home or at work: writing or reading e-mails, searching for work-related information (work) or searching for various issues (home), conduct transactions. *Often:* indicates that worker uses internet for at least one of the above activities every day. < *Often:* indicates that worker uses internet for each of the above activities less than every day. Country characteristics are GDP per capita in 1996 and share of total population living in rural areas in 1996. Individual characteristics are quadratic polynomial in work experience, gender, presence of children, and years of schooling. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 6: Computer Use at Home and at Work

	Panel A: Full Sample			
	Computer use home: Often		Computer use home: < Often	
	Computer use work			
	Often	< Often	Often	< Often
Fixed line diffusion in 1996	5.699***	8.125***	6.960***	6.284***
	(1.699)	(2.084)	(1.604)	(1.831)
Instrument F statistic (from 2SLS)	11.3	15.2	18.8	11.8
Individuals	3,904	2,019	14,615	12,377
Countries	19	19	19	19
	Panel B: Low Internet-Use Sample			
Fixed line diffusion in 1996	20.544	1.860	0.667	1.712
	(12.146)	(6.673)	(2.931)	(1.738)
Instrument F statistic (from 2SLS)	2.9	0.1	0.1	1.0
Individuals	43	173	412	2,623
Countries	17	18	19	19
	Controls in Panels A + B			
Country characteristics	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes

Notes: Ordinary least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Panel A includes full sample, Panel B includes only workers how use internet at home and at work less than every day (see Table 5 for details). ICT skills are normalized with std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Computer use:* how often a person performs the following activities at work: create or read spreadsheets, use word-processing software, use programming language, computer-aided real-time discussions. *Often:* indicates that worker uses computers for at least one of the above activities every day. < *Often:* indicates that worker uses computers for each of the above activities less than every day. Country characteristics are GDP per capita in 1996 and share of total population living in rural areas in 1996. Individual characteristics are quadratic polynomial in work experience, gender, presence of children, and years of schooling. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 7: Returns to ICT Skills: Robustness

Second stage (Dependent variable: log gross hourly wage)									
	Further country controls								No post-com.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ICT skills	0.167**	0.152**	0.156***	0.146*	0.170**	0.151***	0.156***	0.181**	0.090**
	(0.071)	(0.077)	(0.054)	(0.075)	(0.070)	(0.055)	(0.051)	(0.077)	(0.038)
GDP per capita in 1996 (/1000)	0.018***	0.018***	0.018***	0.018***	0.022***	0.021***	0.019***	0.016**	0.016***
	(0.005)	(0.005)	(0.004)	(0.005)	(0.008)	(0.003)	(0.005)	(0.007)	(0.004)
Rural population in 1996	0.071	0.111	–0.066	–0.009	–0.018	0.160	0.118	0.140	–0.103
	(0.730)	(0.679)	(0.651)	(0.639)	(0.540)	(0.809)	(0.624)	(0.773)	(0.416)
Service sector	0.123								
	(0.833)								
Union density		0.182							
		(0.251)							
Employment protection			–0.068						
			(0.064)						
Public sector				0.609					
				(0.703)					
Youth unemployment rate					0.730				
					(1.021)				
Enrollment tertiary education						8.835*			
						(5.201)			
Cable diffusion in 1996							0.402		
							(0.282)		
Mobile diffusion in 2012								–0.002	
								(0.002)	
Individual characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First stage (Dependent variable: ICT skills)									
Fixed line diffusion in 1996	7.977***	7.207***	9.333***	7.782***	8.098***	8.879***	8.270***	7.273***	9.226***
	(1.756)	(1.522)	(1.389)	(1.565)	(1.653)	(1.407)	(1.332)	(1.367)	(1.642)
Instrument F statistic	20.6	22.4	45.1	24.7	24.0	39.8	38.6	28.3	31.6
Individuals	40,865	40,865	40,865	40,865	40,865	40,865	40,865	40,865	35,550
Countries	19	19	19	19	19	19	19	19	16

Notes: Two-stage least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Column (9) is without post-communist countries (i.e., Czech Rep., Poland, Slovak Rep.). Dependent variable in second stage, *log gross hourly wage*, is measured in purchasing power parities. ICT skills are standardized to std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Service sector:* share of service sector in the GDP. *Union density:* share of wage and salary earners who are trade union members. *Employment protection:* employment protection legislation (EPL), composite indicator measuring strictness of employment protection for individual and collective dismissals. *Public sector:* share of workers employed in the public sector. *Youth unemployment rate:* unemployment rate of persons aged 15–24. *Enrollment tertiary education:* share of population currently in tertiary education. *Cable diffusion in 1996:* cable television subscribers per 100 inhabitants in 1996. *Mobile diffusion in 2012:* mobile-cellular telephone subscriptions per 100 inhabitants in 2012. Individual characteristics are quadratic polynomial in work experience, gender, presence of children, and years of schooling. All variables except for ICT skills and individual characteristics are measured at the country level. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. *Data sources:* ITU, OECD, PIAAC, Statistics Canada, UNESCO Institute for Statistics, World Bank.

Table 8: Returns to ICT Skills: Adding Individual-Level Controls

Second stage (Dependent variable: log gross hourly wage)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ICT skills	0.165**	0.165**	0.171**	0.182**	0.167***	0.185**	0.175**
	(0.067)	(0.068)	(0.067)	(0.071)	(0.064)	(0.083)	(0.068)
Experience			0.036***	0.033***	0.034***	0.037***	0.035***
			(0.005)	(0.005)	(0.005)	(0.006)	(0.005)
Experience^2 (/100)			–0.023	–0.020	–0.018	–0.021	–0.020
			(0.020)	(0.019)	(0.021)	(0.020)	(0.020)
Female	–0.051	–0.051	–0.026	–0.012	–0.019	0.056	–0.015
	(0.051)	(0.050)	(0.057)	(0.060)	(0.057)	(0.092)	(0.049)
Children	0.127**	0.127**	0.172***	0.166***	0.170***	0.184**	0.162***
	(0.050)	(0.051)	(0.061)	(0.057)	(0.060)	(0.078)	(0.060)
Years of schooling	–0.042	–0.013	–0.033	–0.031	–0.029	–0.025	–0.033
	(0.043)	(0.038)	(0.041)	(0.039)	(0.037)	(0.033)	(0.039)
Age	0.030						
	(0.019)						
Age^2 (/100)	–0.001						
	(0.032)						
Potential work experience		0.029***					
		(0.006)					
Potential work experience^2 (/100)		0.001					
		(0.031)					
Full-time			–0.039				
			(0.057)				
Parental education				–0.157**			
				(0.073)			
Health					–0.011		
					(0.030)		
Country characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Occupation fixed effects	No	No	No	No	No	Yes	No
Industry fixed effects	No	No	No	No	No	No	Yes
First stage (Dependent variable: ICT skills)							
Fixed line diffusion in 1996	8.236***	8.134***	8.073***	7.633***	8.460***	6.981***	7.856***
	(1.570)	(1.557)	(1.456)	(1.436)	(1.246)	(1.599)	(1.420)
Instrument F statistic	27.5	27.3	30.7	28.3	46.1	19.1	30.1
Individuals	40,865	40,865	40,865	39,060	33,330	40,479	40,369
Countries	19	19	19	19	18	19	19

Notes: Two-stage least squares estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Column (5) is without Canada because the health variable is not reported. Dependent variable in second stage, *log gross hourly wage*, is measured in purchasing power parities. ICT skills are normalized with std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Potential experience:* replaces the quadratic polynomial in actual work experience by a quadratic polynomial in potential work experience (age minus years of schooling minus 6). *Full-time:* 1 = working more than 30 hours per week. *Parental education:* 1 = neither parent attained upper secondary education; 2 = at least one parent attained upper secondary education; 3 = at least one parent attained tertiary education. *Health:* 1 = poor; 2 = fair; 3 = good; 4 = very good; 5 = excellent. In Column (6) (Column 7), we add controls for one-digit occupation categories (one-digit industry categories). Country characteristics are GDP per capita in 1996 and share of total population living in rural areas in 1996. All variables except for fixed line diffusion and country characteristics are measured at the individual level. See Table 1 for details. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table 9: Returns to ICT Skills: Within-Country IV and OLS Estimates

Panel A: Full Sample

Dependent variable: log gross hourly wage	IV (Second Stage)			OLS		
	(1)	(2)	(3)	(4)	(5)	(6)
ICT skills	0.182**	0.229**	0.252***	0.110***	0.109***	0.141***
	(0.082)	(0.091)	(0.091)	(0.015)	(0.015)	(0.014)
Municipality characteristics	No	Yes	Yes	No	Yes	Yes
Individual characteristics	No	No	Yes	No	No	Yes
First stage (Dependent variable: ICT skills)						
Threshold	–0.748**	–0.733***	–0.634**			
	(0.293)	(0.269)	(0.261)			
Instrument F statistic	6.5	7.5	5.9			
Individuals	1,537	1,537	1,537	1,537	1,537	1,537
Municipalities	227	227	227	227	227	227

Panel B: No Own MDF Sample

Dependent variable: log gross hourly wage						
ICT skills	0.276**	0.280**	0.296**	0.105**	0.097**	0.106**
	(0.131)	(0.128)	(0.131)	(0.042)	(0.043)	(0.050)
Municipality characteristics	No	Yes	Yes	No	Yes	Yes
Individual characteristics	No	No	Yes	No	No	Yes
First stage (Dependent variable: ICT skills)						
Threshold	–0.934**	–0.986**	–0.866**			
	(0.332)	(0.372)	(0.382)			
Instrument F statistic	7.9	7.0	5.1			
Individuals	140	140	140	140	140	140
Municipalities	22	22	22	22	22	22

Notes: Sample: West German employees aged 20–49, no first-generation migrants. All regressions use sampling weights. Columns (1)–(3) show instrumental-variable estimates where distance calculations are based on municipalities' geographic centroid. The instrument is a threshold dummy indicating whether a municipality is more than 4,200 meters away from its main distribution frame (MDF) (1=lower probability of DSL availability), and zero otherwise. Instrumental-variable estimation is implemented through Limited Information Maximum Likelihood (LIML), where the user-specified constant (alpha) is set to 1. Fullers (1977) modification of the LIML estimator is used, which ensures that the estimator has finite moments. For comparison, Columns (4)–(6) show least squares estimates. In Panel B, the sample consists of West German municipalities without an own MDF. ICT skills are measured at the individual level and are standardized to std. dev. 1; in Columns (1)–(3) with the municipality-level std. dev. as "numeraire" scale. Municipality characteristics are unemployment rate (i.e., share of unemployed individuals in the working-age population aged 18 to 65) and population share of individuals older than 65. Individual characteristics are quadratic polynomial in work experience, gender, and presence of children. See Table 1 for details. Robust standard errors, adjusted for clustering at the municipality level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* German Broadband Atlas, German Federal Statistical Office, PIAAC.

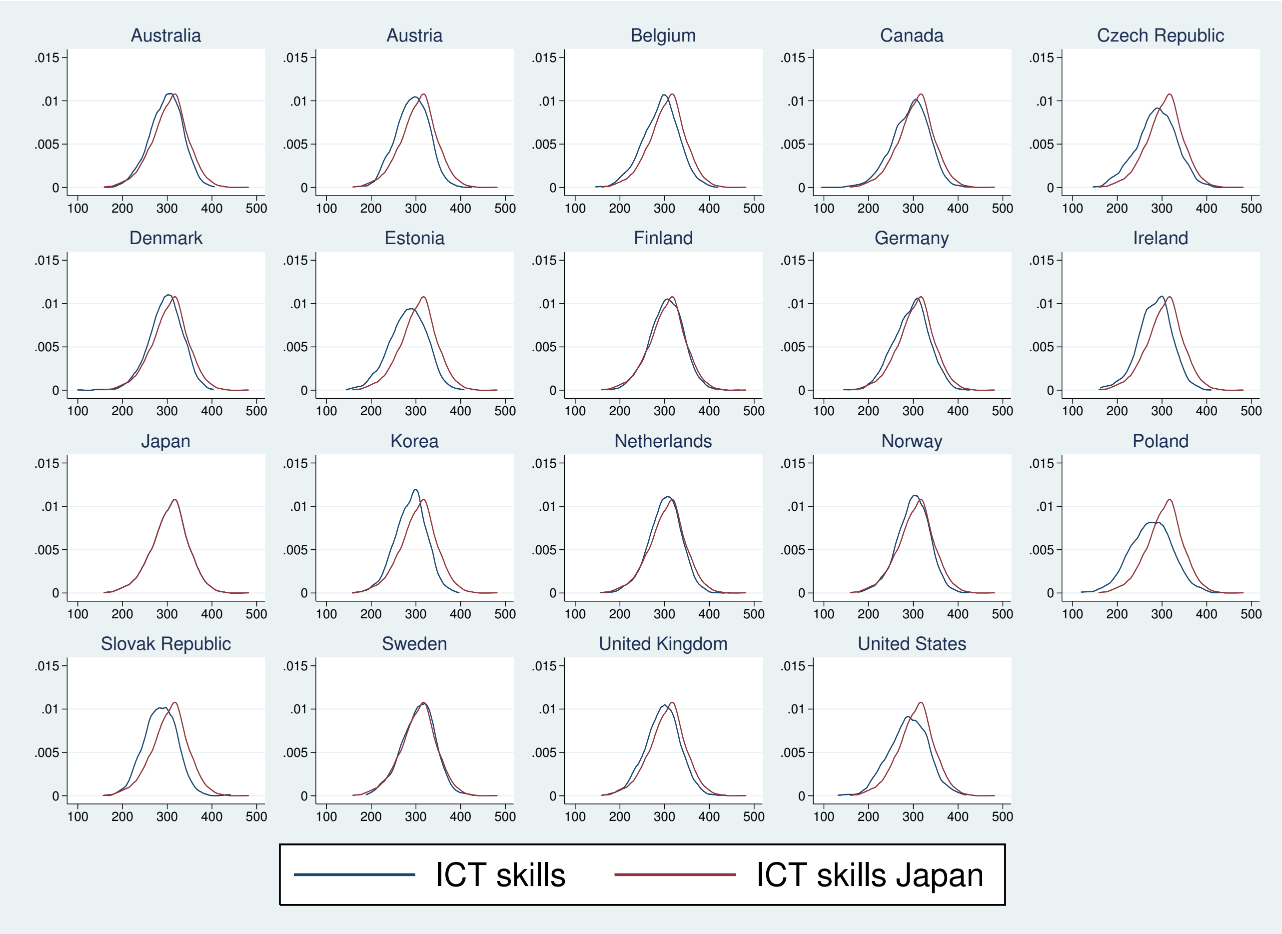
Table 10: Within-Country Placebo Test

	Panel A: Full Sample			
Dependent variable: cognitive skills in				
	Numeracy	Literacy	ICT	ICT
Threshold	0.202	0.022	–0.419***	–0.260*
	(0.124)	(0.155)	(0.138)	(0.152)
ICT skills	0.784***	0.803***		
	(0.020)	(0.020)		
Numeracy skills			0.727***	
			(0.018)	
Literacy skills				0.768***
				(0.018)
R squared (adjusted)	0.59	0.63	0.60	0.64
Individuals	1,537	1,537	1,537	1,537
Municipalities	227	227	227	227
	Panel B: No Own MDF Sample			
Dependent variable: cognitive skills in				
	Numeracy	Literacy	ICT	ICT
Threshold	0.297	0.124	–0.554***	–0.417***
	(0.157)	(0.145)	(0.177)	(0.128)
ICT skills	0.725***	0.777***		
	(0.061)	(0.053)		
Numeracy skills			0.724***	
			(0.057)	
Literacy skills				0.817***
				(0.053)
R squared (adjusted)	0.58	0.67	0.60	0.69
Individuals	140	140	140	140
Municipalities	22	22	22	22
	Controls in Panels A + B			
Municipality characteristics	Yes	Yes	Yes	Yes
Individual characteristics	Yes	Yes	Yes	Yes

Notes: Ordinary least squares estimation weighted by sampling weights. Sample: West German employees aged 20–49, no first-generation migrants. Numeracy, literacy, and ICT skills are measured at the individual level and are standardized to std. dev. 1, using the municipality-level std. dev. as "numeraire" scale. *Threshold:* indicates whether a municipality is more than 4,200 meters away from its main distribution frame (MDF) (1=lower probability of DSL availability), and zero otherwise. Municipality characteristics are unemployment rate (i.e., share of unemployed individuals in the working-age population aged 18 to 65) and population share of individuals older than 65. Individual characteristics are quadratic polynomial in work experience, gender, and presence of children. See Table 1 for details. Robust standard errors, adjusted for clustering at the municipality level, in parentheses. Significance levels: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. *Data sources:* German Broadband Atlas, German Federal Statistical Office, PIAAC.

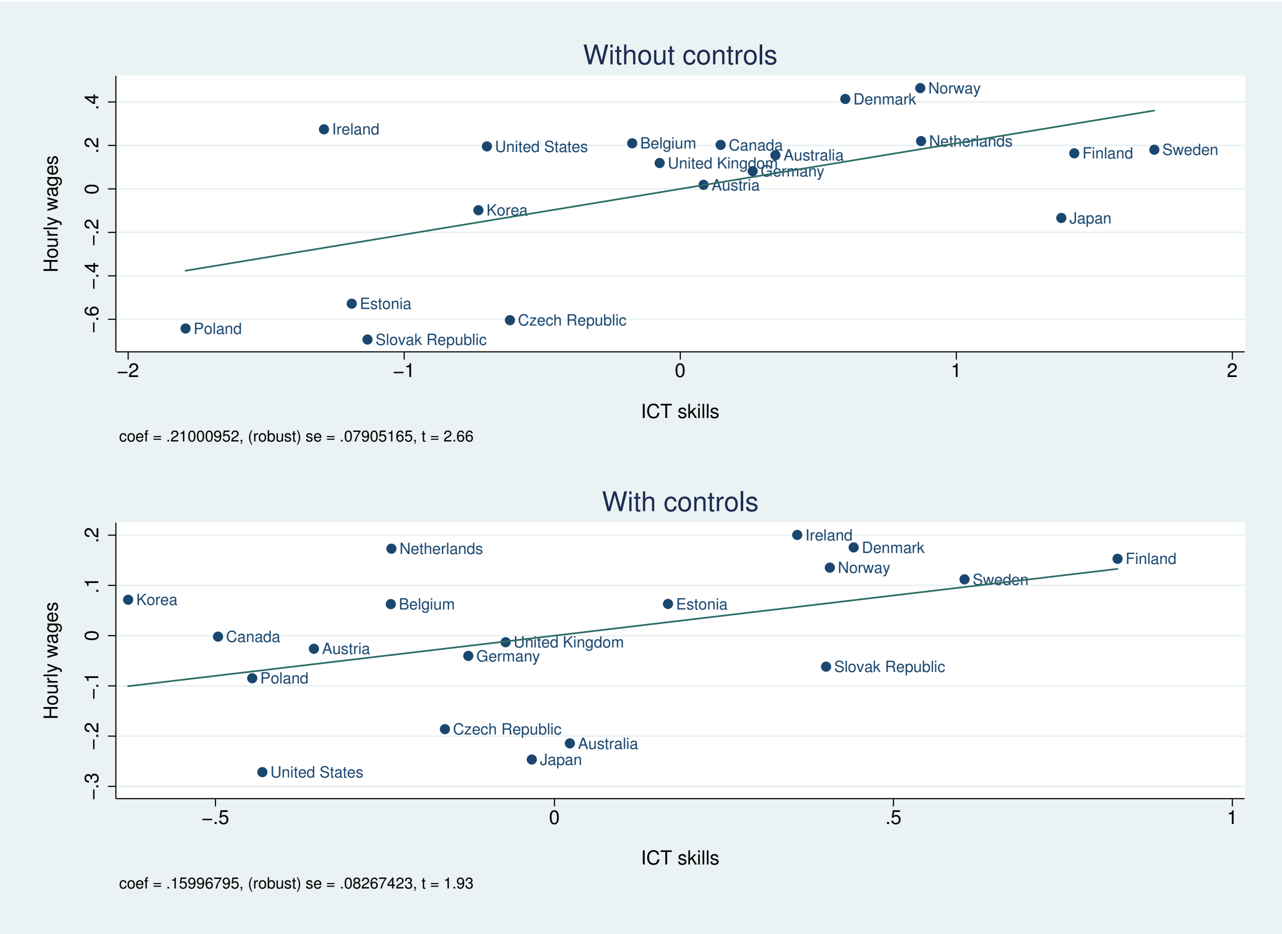
Appendix

Figure A-1: ICT Skills within Countries



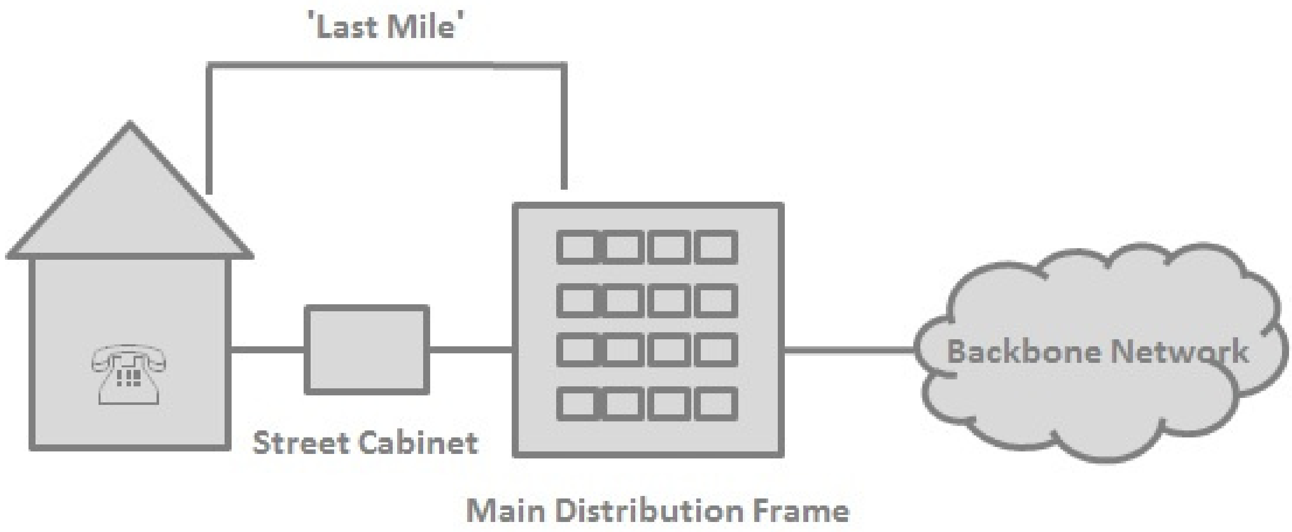
Notes: Smoothed kernel density plots are shown. A kernel density plot of Japan (i.e., the country with highest average ICT skills) in shown in each panel. Sample: employees aged 20–49 (no first-generation migrants). *Data source:* PIAAC.

Figure A-2: Returns to ICT Skills: Country-Level Least Squares Results



Notes: Sample: employees aged 20–49 (no first-generation migrants). All variables are aggregated to the country level. The graph in the top panel does not include any controls. The graph in the bottom panel is an added-variable plot that controls for all variables in Table 2, Column (5). ICT skills are normalized with std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Data sources:* ITU, OECD, PIAAC, World Bank.

Figure A-3: The Structure of a DSL Network



Notes: The figure shows the structure of a DSL network which relies on the "last mile" of the pre-existing voice-telephony network. The "last mile" consists of copper wires connecting every household via the street cabinet to the main distribution frame. At the main distribution frame a so-called DSLAM (Digital Subscriber Line Access Multiplexer) is installed that aggregates and redirects the voice and data traffic to the telcos backbone network.

Table A-1: Descriptive Statistics (Individual-Level Variables)

	Pooled	Australia	Austria	Belgium	Canada	Czech R.	Denmark	Estonia	Finland	Germany
Gross hourly wage	17.7	18.7	16.3	19.2	19.9	9.1	23.6	10.5	18.4	18.5
(in PPP-US-$)	(9.7)	(8.3)	(6.3)	(6.5)	(9.0)	(4.2)	(8.1)	(6.4)	(6.8)	(9.4)
ICT skills	294.0	297.3	291.4	291.0	293.5	287.2	296.5	282.2	304.3	295.4
	(39.8)	(36.5)	(36.1)	(40.2)	(41.3)	(43.9)	(37.5)	(41.0)	(37.9)	(39.6)
Yrs schooling	13.9	14.9	12.7	13.5	13.7	13.7	13.4	12.8	13.5	14.1
	(2.5)	(2.1)	(2.3)	(2.3)	(2.2)	(2.4)	(2.4)	(2.6)	(2.7)	(2.3)
Experience (years)	14.0	14.6	15.4	14.8	15.4	13.0	16.8	12.2	12.8	14.3
	(8.4)	(8.4)	(8.7)	(8.3)	(8.5)	(7.8)	(8.6)	(7.9)	(8.0)	(9.0)
Female (share)	0.48	0.48	0.50	0.49	0.48	0.44	0.50	0.53	0.50	0.47
Children yes/no (share)	0.58	0.48	0.56	0.66	0.54	0.62	0.63	0.65	0.60	0.55
Observations	40,865	1,926	1,667	1,764	7,531	1,594	1,902	2,161	2,013	1,905
	Ireland	Japan	Korea	Netherl.	Norway	Poland	Slovak R.	Sweden	U.K.	U.S.
Gross hourly wage	22.2	15.3	17.0	19.9	24.6	9.4	9.0	18.2	18.9	21.1
(in PPP-US-$)	(11.3)	(9.2)	(13.4)	(8.6)	(8.4)	(5.5)	(6.0)	(5.3)	(11.4)	(12.7)
ICT skills	284.7	305.6	288.5	300.8	299.8	276.0	284.8	305.3	295.2	289.2
	(37.6)	(40.9)	(34.9)	(36.5)	(36.2)	(47.0)	(36.8)	(37.7)	(39.3)	(43.3)
Yrs schooling	16.2	13.8	14.3	14.0	14.8	14.5	14.2	12.8	13.3	14.2
	(2.3)	(2.3)	(2.3)	(2.2)	(2.2)	(2.6)	(2.5)	(2.2)	(2.3)	(2.5)
Experience (years)	14.0	13.5	9.8	14.6	14.6	10.4	12.8	13.7	15.7	15.5
	(8.0)	(7.8)	(6.9)	(8.0)	(8.1)	(7.7)	(8.3)	(8.7)	(8.8)	(8.6)
Female (share)	0.56	0.41	0.44	0.49	0.49	0.47	0.48	0.49	0.48	0.52
Children yes/no (share)	0.51	0.49	0.53	0.52	0.65	0.57	0.58	0.59	0.57	0.61
Observations	1,451	1,676	1,934	1,854	1,980	2,364	1,357	1,595	2,818	1,373

Notes: Means, standard deviations (in parentheses), and numbers of observations for selected variables by country. Sample: employees aged 20–49, no first-generation migrants. Pooled specification gives same weight to each country. *Data source:* PIAAC.

Table A-2: Descriptive Statistics (Country-Level Variables)

	Pooled	Australia	Austria	Belgium	Canada	Czech R.	Denmark	Estonia	Finland	Germany
First emergence of broadband		1999	1999	2000	1999	2000	1999	2000	1999	1999
Fixed line diffusion in 1996	0.49	0.50	0.48	0.46	0.61	0.27	0.62	0.31	0.55	0.54
GDP per capita in 1996	25	28	29	27	29	17	29	8	23	28
Rural population in 1996	0.24	0.14	0.34	0.03	0.22	0.25	0.15	0.30	0.19	0.27
Service sector	0.70	0.69	0.70	0.77	0.70	0.60	0.77	0.67	0.71	0.69
Union density	0.32	0.18	0.28	0.50	0.27	0.17	0.69	0.08	0.69	0.18
Employment protection	2.30	1.99	2.44	3.08	1.51	2.75	2.32	2.07	2.17	2.98
Public sector	0.29	0.25	0.26	0.29	0.33	0.26	0.39	0.30	0.36	0.15
Youth unemployment rate	0.16	0.12	0.09	0.20	0.14	0.19	0.14	0.20	0.18	0.08
Enrollment tertiary education	0.05	0.06	0.04	0.04	0.04	0.04	0.05	0.05	0.06	0.04
Cable diffusion in 1996	0.19	0.02	0.10	0.36	0.27	0.06	0.24	0.44	0.16	0.20
Mobile diffusion in 2012	122.61	105.59	160.54	111.33	80.05	126.85	117.57	160.41	172.32	111.59

	Ireland	Japan	Korea	Netherl.	Norway	Poland	Slovak R.	Sweden	U.K.	U.S.
First emergence of broadband	2000	1999	2000	1999	1999	2001	2000	1999	1999	1999
Fixed line diffusion in 1996	0.38	0.51	0.43	0.54	0.57	0.17	0.23	0.68	0.53	0.62
GDP per capita in 1996	24	29	17	29	40	10	12	25	26	36
Rural population in 1996	0.42	0.22	0.21	0.26	0.26	0.38	0.44	0.16	0.22	0.22
Service sector	0.71	0.71	0.58	0.74	0.57	0.63	0.62	0.73	0.79	0.80
Union density	0.33	0.18	0.10	0.18	0.55	0.15	0.17	0.67	0.26	0.11
Enrollment tertiary education	1.98	2.09	2.17	2.88	2.31	2.39	2.63	2.52	1.71	1.17
Public sector	0.32	0.13	0.16	0.29	0.38	0.22	0.28	0.39	0.34	0.23
Youth unemployment rate	0.33	0.08	0.09	0.09	0.09	0.26	0.34	0.24	0.21	0.16
People in tertiary education	0.04	0.03	0.07	0.05	0.05	0.05	0.04	0.05	0.04	0.07
Cable diffusion in 1996	0.15	0.10	0.15	0.37	0.15	0.07	0.08	0.21	0.04	0.24
Mobile diffusion in 2012	107.21	110.91	109.43	117.97	116.68	140.34	111.91	124.57	135.29	95.45

Notes: Only country-level characteristics reported. *First emergence of broadband:* year in which predicted broadband penetration reaches 1 percent. *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. *Rural population in 1996:* share of total population living in rural areas in 1996. *Service sector:* share of service sector in the GDP. *Union density:* share of wage and salary earners who are trade union members. *Employment protection:* employment protection legislation (EPL), composite indicator measuring strictness of employment protection for individual and collective dismissals. *Public sector:* share of workers employed in the public sector. *Youth unemployment rate:* unemployment rate of persons aged 15–24. *Enrollment tertiary education:* share of population currently in tertiary education. *Cable diffusion in 1996:* cable television subscribers per 100 inhabitants in 1996. *Mobile diffusion in 2012:* mobile-cellular telephone subscriptions per 100 inhabitants in 2012. GDP per capita is expressed in PPP-US-$ (divided by 1000). Pooled specification gives same weight to each country. *Data sources:* ITU, OECD, PIAAC, Statistics Canada, UNESCO Institute for Statistics, World Bank.

Table A-3: Returns to ICT Skills: Instrumental-Variables Estimates (First Stage)

Dependent variable: ICT skills					
	(1)	(2)	(3)	(4)	(5)
Fixed line diffusion in 1996	5.686***	5.765***	5.338***	5.552***	8.075***
	(0.840)	(1.276)	(1.384)	(1.226)	(1.456)
GDP per capita in 1996 (/1000)		–0.002	–0.000	0.009	–0.040
		(0.024)	(0.024)	(0.022)	(0.028)
Rural population in 1996			–0.888	–0.951	–2.274
			(1.182)	(1.014)	(1.920)
Experience				0.042	–0.017
				(0.028)	(0.027)
Experience^2 (/100)				–0.430***	–0.197**
				(0.080)	(0.074)
Female				–0.604***	–0.855***
				(0.131)	(0.108)
Children				–0.829***	–0.771***
				(0.125)	(0.113)
Years of schooling					0.653***
					(0.042)
Instrument F statistic	45.8	20.4	14.9	20.5	30.7
Individuals	40,865	40,865	40,865	40,865	40,865
Countries	19	19	19	19	19

Notes: Table reports first-stage results of two-stage least squares estimations presented in Table 2. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table A-4: Returns to ICT Skills: Cross-Country Simultaneous-Equations Estimation

Third stage (Dependent variable: log gross hourly wage)					
	(1)	(2)	(3)	(4)	(5)
ICT skills	0.362***	0.201**	0.199*	0.194*	0.171**
	(0.085)	(0.091)	(0.109)	(0.099)	(0.069)
GDP per capita in 1996 (/1000)		0.020***	0.020***	0.015**	0.018***
		(0.006)	(0.007)	(0.007)	(0.005)
Rural population in 1996			–0.025	0.016	0.062
			(0.744)	(0.709)	(0.744)
Experience				0.031***	0.035***
				(0.007)	(0.005)
Experience^2 (/100)				–0.000	–0.022
				(0.045)	(0.020)
Female				–0.019	–0.020
				(0.063)	(0.059)
Children				0.196**	0.173***
				(0.093)	(0.063)
Years of schooling					–0.034
					(0.042)
Second stage (Dependent variable: ICT skills)					
Broadband diffusion in 2012	13.464***	13.774**	15.364*	15.955*	23.054*
	(3.299)	(6.360)	(8.956)	(8.847)	(12.095)
First stage (Dependent variable: Broadband diffusion in 2012)					
Fixed line diffusion in 1996	0.422***	0.419***	0.347**	0.348**	0.350**
	(0.070)	(0.133)	(0.139)	(0.139)	(0.139)
Individuals	40,865	40,865	40,865	40,865	40,865
Countries	19	19	19	19	19

Notes: Three-equation seemingly unrelated regression estimation weighted by sampling weights (giving same weight to each country). Sample: employees aged 20–49, no first-generation migrants. Dependent variable in third stage, *log gross hourly wage*, is measured in purchasing power parities. ICT skills are standardized to std. dev. 1 across countries, using the country-level std. dev. as "numeraire" scale. *Broadband diffusion in 2012:* actual diffusion of broadband Internet in 2012 (see Figure 3). *Fixed line diffusion in 1996:* voice telephony penetration rate (telephone access lines per 100 inhabitants) in 1996. Broadband diffusion, fixed line diffusion, GDP per capita and rural population share are measured at the country level; all remaining variables are measured at the individual level. See Table 1 for details on the control variables. Robust standard errors, adjusted for clustering at the country level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* ITU, OECD, PIAAC, World Bank.

Table A-5: Returns to ICT Skills: Within-Country Simultaneous-Equations Estimation

Third stage (Dependent variable: log gross hourly wage)						
	Full sample			No own mdf sample		
	(1)	(2)	(3)	(4)	(5)	(6)
ICT skills	0.223**	0.244**	0.273**	0.303**	0.307**	0.331**
	(0.107)	(0.103)	(0.106)	(0.154)	(0.151)	(0.160)
Municipality characteristics	No	Yes	Yes	No	Yes	Yes
Individual characteristics	No	No	Yes	No	No	Yes
Second stage (Dependent variable: ICT skills)						
Broadband availability	9.536**	12.882**	11.158**	19.785	21.064*	18.550*
	(4.279)	(6.010)	(5.109)	(12.499)	(11.958)	(10.210)
First stage (Dependent variable: Broadband availability)						
Threshold	–0.069***	–0.057***	–0.057***	–0.047*	–0.047**	–0.047**
	(0.019)	(0.019)	(0.019)	(0.026)	(0.022)	(0.022)
Individuals	1,537	1,537	1,537	140	140	140
Municipalities	227	227	227	22	22	22

Notes: Three-equation seemingly unrelated regression estimation weighted by sampling weights. Sample: West German employees aged 20–49, no first-generation migrants. Columns (1)–(3) show results for all West German municipalities; Columns (4)–(6) restrict sample to West German municipalities without an own main distribution frame (MDF). ICT skills are measured at the individual level and are standardized to std. dev. 1, using the municipality-level std. dev. as "numeraire" scale. *Broadband availability:* share of households in a municipality for which broadband Internet is technologically available (measured in 2008). *Threshold:* indicates whether a municipality is more than 4,200 meters away from its MDF (1=lower probability of DSL availability), and zero otherwise. Municipality characteristics are unemployment rate (i.e., share of unemployed individuals in the working-age population aged 18 to 65) and population share of individuals older than 65. Individual characteristics are quadratic polynomial in work experience, gender, and presence of children. See Table 1 for details on the control variables. Robust standard errors, adjusted for clustering at municipality level, in parentheses. Significance levels: * p<0.10, ** p<0.05, *** p<0.01. *Data sources:* German Broadband Atlas, German Federal Statistical Office, PIAAC.