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Abstract

Face-to-face contact, even temporary one, helps researchers form personal ties and transfer tacit knowledge. The ability of researchers to colocate, including attendance at international conferences, workshops and seminars, is affected by the administrative barriers to international mobility. This paper uses a gravity-style empirical framework to examine the link between international knowledge flows and immigration policies. The results suggest that the paper walls erected by such policies reduce not just the mobility of individuals, but also the diffusion of knowledge. A moderately restrictive mobility barrier reduces incoming and outgoing knowledge flows by about 0.8-1.3% per year. The effect of knowledge-exporting country's policy persists for nearly 10 years. There is also a short-term asymmetry: diffusion of recent knowledge is affected more by the immigration policy of a knowledge-exporter rather than a knowledge-importer.

Keywords: diffusion of knowledge; academic mobility; immigration policy; visa policy.

JEL codes: F10, F29, O33, R10.

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1 Introduction

Knowledge flows, though intangible, sometimes leave a 'paper trail' in the form of citations to patents or academic publications (Jaffe et al. 1993). A citation does not necessarily reflect transfer of knowledge and not every knowledge flow is reflected in a citation, but the paper trails and their absence can be used to understand the diffusion of knowledge. Empirical studies have shown that diffusion of knowledge can be described by a gravity-based framework using factors that have been shown to affect the flows of goods and services, FDI and people (e.g. MacGarvie 2005; Peri 2005; Drivas and Economidou 2015). A common finding is that physical proximity, common language and border are associated with better diffusion of knowledge. The relative importance of these factors is smaller for knowledge flows than for trade, FDI or migration due to the 'weightless' and tariff-free nature of knowledge, which reduces the transaction costs and allows knowledge to reach farther than trade or migration (Peri 2005).

At the same time, there is a large literature showing the importance of colocation and localised knowledge spillovers (e.g. Jaffe et al. 1993; Collins 1974; Agrawal and Goldfarb 2008). One of the benefits of colocation is that it allows authors to develop personal ties, which facilitate transfer of knowledge through the social research network (Jöns 2009; Jonkers and Cruz-Castro 2013; Head et al. 2015). The importance of social networks has been also shown to facilitate trade and FDI (e.g. Rauch 2001; De Simone and Manchin 2012). However, development of such research networks and personal ties requires some face-to-face contact. The effect of colocation on collaboration and knowledge transfer has been documented in specific subject domains (Collins 1974; Collins 2001) and observed in (natural) experiments (Boudreau et al. 2017; Catalini 2015; Iaria and Waldinger 2015).

The ability of researchers from different countries to colocate temporarily will depend on factors that affect the mobility of researchers, including administrative barriers in the form of immigration policy and travel visa restrictions. These man-made paper walls have been shown to influence the flows of trade, FDI, migration and academic mobility (McKenzie 2007; Neumayer 2011; Umana Dajud 2014; Czaika and Haas 2016; Appelt et al. 2015).

This paper examines whether the administrative barriers to mobility influence the direction and magnitude of international knowledge flows. In principle, knowledge can flow across borders without any restrictions.[1] However, transfer of tacit and recent knowledge may require face-to-face contact between the researchers (Collins 1974; Collins 2001), which in turn depends on their mobility. Paper walls raise the cost of researcher mobility, limiting opportunities for face-to-face contact

[1] One exception could be for weapons- or military-related research, but the diffusion of knowledge in such heavily-regulated domains requires a more specialised analysis.

and development of cross-border research networks. For example, travel visa requirements increase the cost of temporary colocation[2] or even make it impossible (e.g. visa application processing time can make it impossible to attend events on a short notice), reducing opportunities for development of personal ties, such as attending foreign conferences or presenting work at research seminars abroad. Opportunity for informal, face-to-face communication can be important for diffusion of knowledge (Trippl 2013; Wang 2015; Catalini 2015; Iaria and Waldinger 2015; Collins 2001; Collins 1974).

The analysis takes into account barriers to high-frequency mobility (e.g. seminar or laboratory visits for a brief period of time) and low-frequency mobility (e.g. long-term migration). Information on travel visa requirements is used to proxy barriers to high-frequency mobility, while immigration policy towards skilled workers and students will proxy barriers to low-frequency mobility. These barriers have been shown to matter for mobility of scientists and their collaborations (Appelt et al. 2015; Mavroudi and Warren 2013; Kõu and Bailey 2014).

Identifying the effect of administrative barriers is complicated by correlation between the strictness of a policy and physical or cultural distance between countries. The determination of migration policy is driven by macro-level considerations, often of a political or security-oriented nature (Luedtke et al. 2010; Neumayer 2010; Lawson and Lemke 2011; Czaika and Haas 2016), hence from the perspective of knowledge flows the immigration policy towards skilled workers can be seen as source of exogenous variation. For example, if country A imposes a visa restriction on country B based on security considerations, then the cost of face-to-face contact between researchers from A and B will increase, but the policy does not make knowledge generated in countries A and B less relevant.[3] Adding controls for various country, country-time and country-pair factors, this exogeneity of immigration policy helps to identify the effect of administrative restrictions to mobility on the direction and magnitude of knowledge flows. If knowledge's paper trail goes right through the paper walls, then the role of researcher mobility in diffusion of knowledge is likely to be small.

Specifically, the paper explores how immigration policy of the country in which knowledge flow originates (i.e. country of affiliation of the cited author, referred to as 'knowledge-exporting' country) affects its outbound knowledge flows. Do (entry) barriers to mobility at a destination country (i.e. country of affiliation of the citing author, referred to as 'knowledge-importing' country) also reduce

[2]Ng and Whalley (2008) give examples of visa or work permit application costs, including processing time, for several countries, and estimate the global cost of the visa system to be about 0.3% of world GDP. The cost of a passport also varies across countries and can be substantial, see McKenzie (2007).

[3]In the long-term it's possible that lack of contact between researchers in two countries can lead to an increase in their cognitive distance, reducing knowledge flows further.

inflows of knowledge from other sources? By controlling for knowledge diffusion costs through standard controls used in the literature (physical distance, common language/border and fixed effects to capture other sources of heterogeneity) and exploiting the variation in administrative barriers to mobility, the paper argues that there is a link between bilateral knowledge flows and barriers to mobility.

Knowledge flows are tracked via publication-level citations among economists.[4] The information on citations is taken from Thomson Reuters' Web of Science database for over 430 thousand publications in Economics and almost 6 million cited-citing publication pairs. The dataset includes information on the country of affiliation of all cited and citing authors, but unfortunately, publications prior to 2008 do not explicitly match each author to their respective affiliation. By aggregating citations to the country-level it is possible to track aggregate international knowledge flows without identifying individual author affiliations.

Information on the administrative barriers comes from a new dataset, DEMIG POLICY, which contains information on more than 6'500 policy changes in 45 countries over 1721-2014 period, see DEMIG (2015) and further description in Section 3. This dataset was used to construct country-specific indexes of immigration barriers for skilled workers and students. These indexes are then used to examine whether changes in the barriers to mobility affect the magnitude and direction of knowledge flows between country pairs. The results suggest that increased barriers to immigration of skilled workers and students are associated with reduce incoming and outgoing knowledge flows. A placebo test do not reject a causal link from paper walls to knowledge flows. Robustness checks include a measure of barriers to high-frequency mobility, travel visa requirements. The data on travel visa requirements comes from Neumayer (2011), who collected it from IATA's 2004 Travel Information Manual.

The main contribution of the paper is in showing that administrative barriers to mobility of the skilled also distort knowledge flows. This effect is estimated to be about 0.8-1.3% per year for a moderate increase in barriers. The results show that the effect barriers is more important for flows of recent knowledge, as proxied by citations to papers published at most 1 year ago, with gradual decrease of the coefficients as the citation lag increases to 10 years and more. Finally, the effect of knowledge-exporting country's immigration policy towards skilled workers and students is persistent, having a significant impact for about 9 years.

The remainder of the paper is organised as follows. The next section provides a summary of related literature and how the current paper contributes to the literature. Section 3 describes the data used in the paper. The framework used for estimating the effects of administrative barriers is explained in Section 4, while the results and robustness checks are presented in Section 5. The final section con-

[4]The author is working on creating the dataset that will include other disciplines.

cludes with a discussion of the findings and their policy implications. Additional tables are collected in the appendix.

2 Related literature

The research in this paper relates to several strands of the literature on the diffusion of knowledge and academic mobility. The first strand is on the impact of various geographic, cultural, informational and economic barriers on the diffusion of knowledge. Another strand is the importance of administrative restrictions to mobility for various economic outcomes, such as trade, FDI, migration and academic mobility. These two strands are linked by a third strand that examines the impact of academic mobility and colocation on the flow of knowledge.

The diffusion of knowledge has been tracked in the literature by patent citations and scientific article citations. One of the big research questions has been on the role of distance in the diffusion of knowledge, with a general conclusion that distance has a negative effect on the diffusion of knowledge (e.g. Drivas and Economidou 2015). A recent paper by Head et al. (2015) shows that the role of distance declines after personal ties between authors are taken into account. However, distance still matters to the extent it affects the social network. Improvements in telecommunications lower the communication costs for distant collaboration, but face-to-face interaction appears to be a complement, rather than a substitute for electronic communication (Agrawal and Goldfarb 2008). Another example on the role of distance can be seen in Agrawal, Galasso, et al. (2016) who examine the connection between road infrastructure and innovation and find that better transportation infrastructure allows innovators to access more distant knowledge inputs. This access increases their innovative activity: a 10% increase in the stock of highways causes almost 2% increase in regional patenting over a five-year period.

Factors often used in the empirical gravity literature include common language and common border. MacGarvie (2005) examines how patent citations are affected by the stocks of patent counts, physical distance, common language, FDI, telephone communications, and the 'vintage' of a citation (year of the cited patent). Common language and FDI were found to enhance diffusion of knowledge (for FDI the effect is significant only between technologically-similar countries). The effect of distance is negative, but its importance declines over time.

Several recent studies examined the role of travel visa requirements on mobility. Czaika and Haas (2016) used information on visa restrictions in 38 countries over 1973–2012 period to examine the effect of visas on international migration. They found that visa restrictions significantly decrease circulation of residents of different countries, encouraging long-term settlement in the destination country. This is particularly interesting in the context of network formation, because it

suggests that visa restrictions might have positive effect on the size of diasporas.[5] Czaika and Haas (2016) also report the asymmetric responses to visa introduction/removal: introduction of visas affects the bilateral flows with a significant lag (20% after 10 years), while removal of a visa requirement leads to a much quicker increase in the bilateral flows (30% increase after 3 years).

Appelt et al. (2015) examine the role of travel visa requirements on scientists. They report negative effect of visas on mobility and number of cross-border collaborations. The effect of mutual visa restrictions on international collaborations is more than double the effect of only one country imposing a restriction. A possible interpretation of this is that unilateral visa still permits migration of scientists towards the country that does not impose the restriction, hence international research networks can still form. Once the second visa restriction is implemented, such one-directional flows cease, which limits the development of bilateral research network and leads to reduced number of scientific collaborations. This result contrasts with Neumayer (2011)'s finding that the effect of bilateral visa restrictions on FDI differs only marginally from unilateral visa restriction. The explanation offered in Neumayer (2011) is due to the asymmetry of FDI, with one country responsible for most of the FDI, which reduces the impact of the second visa requirement. This could also be an appropriate description of the asymmetry of knowledge flows, especially between a technologically-advanced country and a catching up country, however Appelt et al. (2015)'s result suggests that visa-less flow in one direction could still allow bilateral collaborations.

Reduced academic mobility is likely to have a negative impact on development of personal ties and informal collaborations. Mavroudi and Warren (2013) conducted interviews with non-European Economic Area postgraduate students and staff at UK universities and report the constraining effect of immigration policy on the mobility of highly-skilled workers and students.

Literature on academic mobility emphasises its role in development of research networks, which in turn have been shown to facilitate the diffusion of knowledge. Mobile academics help to develop research networks both at the destination and at the origin. An interesting case study looked at US Fulbright Fellowship recipients (Kahn and MacGarvie 2016), who are required to return to their home country after completion of studies. By comparing the returnees' performance to that of similar scientists that remain in the US, Kahn and MacGarvie (2016) show that returnees are more frequently cited at home (than similar foreign-born scientists in the US) and direct their own citations towards home-country articles. At the same time, returnees continue citing US-based authors, at least in the short/medium term after they return. Finally, foreign-born scientists in the US were found to attract a higher proportion of potential citations from their home countries than

[5] Also see Ackers (2005) for an interesting discussion on 'scientific' diasporas.

from third countries. This is also indicative of the positive role of research networks in the diffusion of knowledge. Other empirical studies support this finding for research networks at the destination (e.g. Franzoni et al. 2012) and at the origin (e.g. Wang 2015).

Using survey data on almost 2000 international academic visitors to Germany, Jöns (2009) argues that visits from foreign researchers to post-World War II Germany helped to reintegrate Germany into the global scientific community. In addition to collaborations, international visitors provided personal ties/contacts which helped to increase academic mobility and further collaborations by German scientists. A similar observation was reported by Guth and Gill (2008), who interviewed PhD students and researchers from Poland and Bulgaria. The role of personal ties shows up in their study, many PhD students that studied abroad reported that their supervisor provided information on opportunities abroad. The power of networks in determining which scientists migrate is also discussed in Ackers (2005).

Borjas and Doran (2012) examine a natural experiment related to the collapse of the USSR. The influx of Soviet mathematicians into the United States resulted in a crowding out of US-based mathematicians whose research overlapped with that of the Soviet researchers. Another study that examined this historical episode from the perspective of knowledge flows is by Abramitzky and Sin (2014). Abramitzky and Sin (2014) use information on book translations, highlighting their purpose of transmitting knowledge between languages, over the period from 1980 to 2000 as a proxy for diffusion of broad knowledge, and find increased flows of Western knowledge into the former Satellite countries following the decline of communism.

Academic mobility is also important for temporary visits, allowing distant collaborators to work face-to-face. There is evidence on the importance of colocation in physics (Collins 1974; Collins 2001). For example, Collins (2001) describes inability of scientists at Caltech, Stanford and Glasgow (among other universities) to reproduce documented results of research by Russian scientists. After about twenty years since the original publication, Glasgow scientists managed to reproduce the results, but only through close, face-to-face collaboration that necessitated exchanging visits between Russian and Scottish laboratories. There were various elements of tacit knowledge that were not captured by the published results, and accessing such knowledge required face-to-face collaboration. In the present paper, the effect of barriers to mobility should capture the increased cost of international collaborations. Modern technology allows for cheap and nearly instant communication, establishing contacts (and trust) is still enhanced by colocation (cf. Agrawal and Goldfarb 2008; Head et al. 2015).

In related research, Boudreau et al. (2017) examine collaborations of researchers after exposing a random subset of test subjects to colocation and face-to-face in-

teractions. The probability of the treated subjects' collaboration increased by 70%. This suggests that barriers to academic mobility may significantly decrease collaborations and the diffusion of knowledge. A similar effect of colocation on collaborations has been shown for an interesting natural experiment, temporary relocation of scientific workers due to asbestos removal in Paris, which lead to greater collaboration for the (temporarily) collocated research labs (Catalini 2015). The international flows of knowledge can also be disrupted by events that prevent communication between researchers from different countries, Iaria and Waldinger (2015) show that World War I had a large impact on the flows of knowledge between the countries from the opposing camps. Longer research visits or permanent academic migration also stimulate the diffusion of knowledge, for example Azoulay et al. (2012) find that relocation of scientists increases academic citations to their prior work from the new location.

An important methodological question is whether citations can be used to track knowledge flows. Although, the extent to which citations accurately reflect cognitive influences has been questioned (Collins 1974, p. 170), they do capture some elements of knowledge flows. It's true that focus on (visible) citations can result in omission of less visible intellectual influences that could result in transfer of tacit knowledge. There is no clear way to measure the tacit knowledge exchanges, but if tacit knowledge flows complement, rather than substitute, the more visible flows, then the aggregated citation information should also capture at least part of such flows. There are also studies of the social influences on citation behaviour, which find that even though social proximity can influence citations, the authors cite widely outside of their social circle and the citation behaviour is driven by the cognitive relevance of the cited work (Baldi 1998; Johnson and Oppenheim 2007; White et al. 2004).

3 Data and descriptive statistics

The dependent variable, bilateral flow of knowledge, is proxied by aggregate citation count per year between pairs of countries. This data is obtained from Thomson Reuters' Web of Science (WOS), by examining the country of affiliation of all authors of the citing and cited publications in Economics.

The data includes approximately 430 thousand articles published in Economics journals indexed by Web of Science with information on 5.6 million citations (not limited to Economics journals). To construct the gross citation counts at country-pair level the following procedure was used: for every publication, the affiliations of authors were processed to identify the countries of affiliation, which were then assigned to the publication. This procedure allows for multiple affiliations per author, since each document can be associated with multiple countries. After this

procedure, each publication is associated with a set of countries. Combining this data with the information on citations (citing-cited document pair), the aggregate citation count was calculated from 1980 to 2015 for all country pairs in the sample. Citation between documents associated with multiple countries was assigned to all pairwise combinations of the cited and citing document's countries.

The bilateral aggregate citation matrix is sparse, with a lot of zero observations, see Table 1. Any analysis that would focus just on the observed (positive) knowledge flows is likely to be subject to the selection effect, because the estimation will be based on a sample that is not randomly selected. To address the selection effect the estimations are done using Poisson regressions, see Section 4.

Table 1: Number of country-pairs by the presence of knowledge flows.

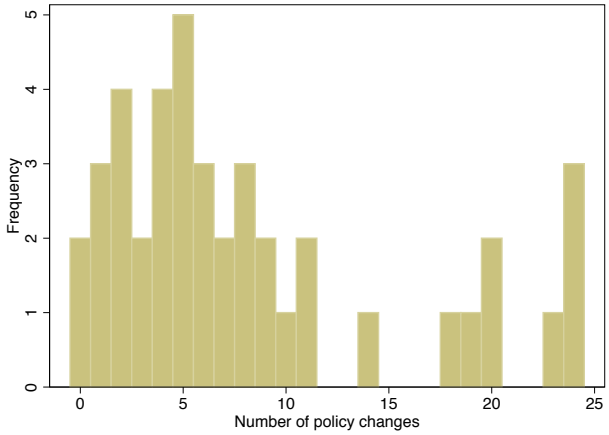
	Number of country pairs	Share of total
Knowledge flows in both directions	3649	17.1
Knowledge flows in one direction only	2217	10.4
No observed knowledge flows	15455	72.5

Notes: knowledge flows are calculated as the sum of all citations between the cited and citing country over 1990-2015; this means that within any single year the number of countries with zero knowledge flows is likely to be larger.

The data on administrative barriers to mobility comes from two independent sources — International Immigration Institute's DEMIG POLICY dataset and International Civil Aviation Association's November 2004 Travel Information Manual. DEMIG POLICY is a recently-released dataset which contains detailed information on approximately 6500 migration policies in 45 countries from 1721 to 2014 (DEMIG 2015). The sample coverage prior to 1990 varies by country, and bulk of the observations are in 1945-2013 period. Each country's policy measure is categorised depending on the target group (all migrants, skilled, low-skilled, students, irregular migrants and other categories), the importance of the policy (low, medium, high), its impact on restrictiveness (neutral, more/less restrictive) and several other important characteristics. Figure 1 shows the distribution of the number of policy changes over 1990–2014.

This dataset is used to construct a country-specific index of administrative barriers to the mobility of skilled workers and students. The index takes into account policies that regulated legal entry and stay, integration, or border and land control as follows: for every country the index is initialised at zero and for subsequent years the index is increased (decreased) by 0.5 if a more (less) restrictive policy of medium importance was implemented or by 1 if a more (less) restrictive policy of high importance was implemented. Table 2 gives examples of moderate changes in policies, and Figure 2 shows variation of index across time for five

Figure 1: Number of changes in the policy towards skilled workers and students over 1990–2014.



Notes: the vertical axis shows the number of countries that have experienced the number of policy changes given on the horizontal axis, as recorded in DEMIG POLICY dataset.

countries with the largest number of changes.

Table 2: Examples of moderate changes in immigration policy.

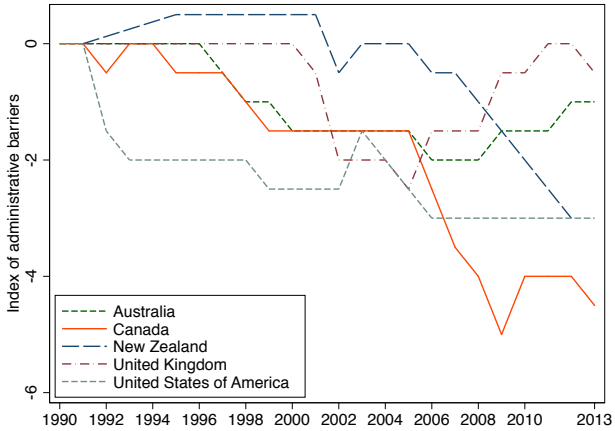
Index	Description	Country, year
+0.5	Fee on recruitment of skilled workers from abroad	Indonesia, 2003
	Quota on foreign workers	India, 2009
	High-skilled immigration programme terminated	Czech Republic, 2010
	Introduction of minimum salary for foreign workers	India, 2010
	Entry visas for highly-skilled abolished	Norway, 2013
-0.5	Fast-track work permits for high-skilled	United Kingdom, 2000
	EU Blue Card implementation	Spain, 2009
	High-skilled are exempt from quota	Russia, 2010
	Visitor visa for academics	New Zealand, 2011
	Quicker procedures for sponsors of high-skilled migrants	Netherlands, 2013
	Introduction of a 'talent visa' for skilled workers	China, 2013

Note: policy descriptions are based on DEMIG (2015).

Many countries have reduced barriers towards skilled workers over the sample period. Countries that maintained (or increased) their barriers experienced lower growth rate in their knowledge exports (incoming citations), see Figure 3. This simple correlation suggests that there may be a link between diffusion of knowledge and the immigration policy towards skilled workers and students.

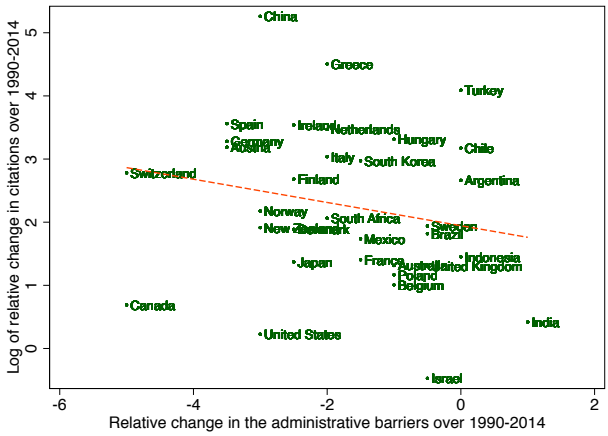
Another measure of the barriers to mobility comes from Neumayer (2011), who extracted information on visa requirements from a November 2004 edition of the manual used in the aviation industry, IATA's Travel Information Manual. This information is available only for year 2004 and only at a symmetric dyad-level,

Figure 2: Indexes of administrative barriers towards skilled workers and students over 1990–2014 for the countries with the greatest number of policy changes.



Notes: the vertical axis shows the index of administrative barriers towards skilled workers and students, a higher number indicates greater barriers (see text for further details); the indexes are country-specific, so their values can be compared within a country across time, but not across countries in a given year.

Figure 3: Relative change in knowledge exports and administrative barriers for the highly-skilled workers and students over 1990–2014.



Notes: the vertical axis shows the logarithm of the relative change in the number of times a country has been cited (i.e. a paper with at least one author claiming affiliation inside the country has been cited by authors from another country); the horizontal axis shows the difference between the value of an index of administrative barriers for the skilled workers and students in 2014 and 1990; the dashed line corresponds to a linear prediction.

i.e. without information on the direction of visa restrictions. For example, in the dataset a unilateral visa dummy is equal to 1 if either country A imposes visa restriction against country B or vice versa, but not both.

Table 3: Average bilateral knowledge flows by visa restrictions.

	Average bilateral citation count			
	Mean	Standard deviation	Share of zero flows	N
No visa restrictions	19.50	215.5	64.2	3178
Unilateral visa restriction	1.07	20.9	82.7	6526
Bilateral visa restrictions	0.80	30.1	89.3	8605
Missing visa information	22.28	942.8	95.7	3012
After removing the United States from the sample				
No visa restrictions	7.90	50.3	64.8	3144
Unilateral visa restriction	0.29	2.7	83.8	6420
Bilateral visa restrictions	0.40	7.7	89.7	8554
Missing visa information	5.25	116.6	95.8	2997
After removing EU28 countries from the sample				
No visa restrictions	6.54	122.6	81.8	1961
Unilateral visa restriction	1.14	24.3	87.5	4699
Bilateral visa restrictions	0.72	33.3	91.6	6694
Missing visa information	21.72	1012.2	96.7	2577

Notes: visa information is based on year 2004 data, the average (undirected) bilateral citations are calculated over 2005-2008 period; unilateral visa restriction means that only one of the two countries in a country pair imposed a visa restriction, while bilateral visa restriction means that both countries in a country pair imposed visa restrictions on each other.

Table 3 shows the average bilateral citation count for 2005–2008 period by visa restrictions of the country pair. The largest volume of knowledge flows, proxied by bilateral citation counts, occurs between countries that have no mutual visa restrictions. On average, countries with visa restrictions cite each other fewer times, and the second visa requirement is associated with a smaller drop in bilateral knowledge flows.[6]

The descriptive statistics show that both measures of barriers to mobility are associated with reduced knowledge flows, but these patterns could be misleading because barriers to mobility are correlated with a range of other variables that affect diffusion of knowledge. The following section describes the framework for identifying the impact of barriers to mobility.

[6]There could be a meaningful difference in the *direction* of flows, but the travel visa information from Neumayer (2011) is coded at dyad-level and is symmetric by design which does not allow distinguishing the direction of flows.

4 Empirical framework

The empirical framework used to examine the link between administrative barriers to mobility and bilateral knowledge flows is similar to approaches used by Appelt et al. (2015) and Head et al. (2015).

The stock of knowledge in each country accumulates over time, providing intellectual capital for researchers at home and abroad. Countries with a larger stock of knowledge have greater capacity to 'export' knowledge abroad. However, the volume of knowledge flows will also depend on the absorptive capacity of the knowledge-importing country, reflecting how actively its own stock of knowledge is growing. There will be other factors that affect the volume of knowledge flows, reflecting communication and collaboration costs between different countries. These negative factors can be mitigated by academic mobility, giving researchers opportunity to develop research networks, to participate in international collaborations, to develop personal ties through face-to-face contacts and colocation.

The mobility of academics will be affected by immigration policies, especially towards skilled workers and students.[7] For example, if two countries are relatively restrictive in their immigration policy, then the researchers from these countries will find it costly to develop personal ties and collaborate across borders, both of which are important for transfer of tacit and/or recent knowledge. This means that a country's strict immigration policy makes it more difficult/costlier to access knowledge inside the country. At the same time immigration policy increases cost of accessing knowledge in other countries by restricting or increasing the cost of foreign researchers visiting the country.

To model the above framework empirically, consider the flow of citations from country i (citing country) to country j (cited country) in year t, $F_{ij,t}$, which indicate that knowledge is flowing from the cited to the citing country in year t. The flow of citations will depend on the stock of knowledge available in the cited country, $K_{j,t}$, and the absorptive capacity of the citing country i, $A_{i,t}$. This flow will be affected by the cost of knowledge transfer, $C_{ij,t}$.

$$F_{ij,t} = A_{i,t}^{\alpha} K_{j,t}^{\kappa} C_{ij,t}^{-1} \tag{1}$$

Equation 1 implies that bilateral knowledge flow will be zero when there is no absorptive capacity in an economy ($A_{i,t} = 0$), when there is no knowledge to import from a destination ($K_{j,t} = 0$), or when the cost of knowledge transfer is infinitely great.

The flow of knowledge will be proxied by citations to academic publications among economists, representing transfer of knowledge from the cited country j

[7] During the study period, international students will acquire knowledge developed at their destination country, and will be referring to this knowledge upon return.

to citing country i in year t (the year of publication of the cited paper).[8] In practice, not all citations will reflect transfer of knowledge and some transfers of knowledge may not leave a paper trail in the form of a citation, including transfer of tacit knowledge or knowledge that could not be used by the recipient. Aggregate citations are only a proxy for knowledge flows and as long as the measurement error is unrelated to barriers to mobility, the error will reduce the efficiency of estimates, without introducing bias.

The absorptive capacity of country i, $A_{i,t}$ will be proxied by the quantity of new papers published by country i in year t. The stock of knowledge in the cited country, $K_{j,t}$ will be proxied by the (cumulative) stock of publications in country j at time t. This choice of proxies is primarily motivated by the source of the data (citations on academic papers), but the distinction between stocks and flows does not change the results due to high correlation between the stock of existing papers and the number of new papers published. Other valid proxies could be considered, for example the absorptive capacity could be approximated with the number of researchers in a given country, while the stock of knowledge could be proxied by the number of existing patents (capturing a more practical implementation of knowledge).

Finally, the influence of administrative barriers to mobility and other factors that can affect diffusion of knowledge will be collected in cost factor, $C_{ij,t}$. Similar to Head et al. (2015), the cost factor will be modelled as an exponential function of time-varying administrative barriers to mobility, time fixed effects and time-invariant country-pair heterogeneity, e.g. distance, common language and such.[9]

Identification strategy

The following equation (or its log-transformed version) will be used for estimation:

$$F_{ij,t} = exp(\alpha \log A_{i,t} + \kappa \log K_{j,t} - \log \mathrm{C}_{ij,t}). \tag{2}$$

The estimated coefficients will not necessarily indicate a causal relationship, moreover they could be biased. The strategy for identifying the causal impact of higher costs of face-to-face collaboration will rely on a source of exogenous variation in the cost of international colocation by nationals of a country — immigration policy towards skilled workers and students (including origin and destination policies) and travel visa requirements. These measures of administrative barriers to

[8] As a further distinction it is possible to track the year of the paper to which the citations are made. Such distinction allows controlling for 'vintage' effects, see MacGarvie (2005). The time gap between the cited and citing papers can convey important information about the speed of knowledge diffusion, see Table 5.

[9] The data on dyad-specific variables is taken from Neumayer (2011), who in turn used data from Mayer and Zignago (2011).

mobility are exogenous from the perspective of scientific collaborations, because imposition (or removal) of such 'paper walls' is guided by political, macroeconomic and security-based considerations (e.g. Luedtke et al. 2010; Neumayer 2006). The rationale behind the processes underlying imposition and removal of 'paper walls' also addresses the reverse causality concern, suggesting that the reverse causal effect of knowledge flows on migration policy is likely to be small, if any. As a robustness check for the direction of causality leading values of policy will be included as a 'placebo' treatment. Significant coefficients on the leading policy variables would reject a causal link between knowledge flows and policy.

Another concern could be the bias due to omission of variables that affect both the dependent variable (bilateral knowledge flows) and the variable of interest (administrative barriers). One candidate, based on the large literature on localised knowledge spillovers, is physical proximity. Countries that are located close to each other are likely to have larger bilateral knowledge flows and also are likely to have more favourable migration policy towards each other. To ensure that the potential omitted variable bias is minimised the variables that are typically used in the empirical gravity literature are included in the estimations, these variables include colonial link in the past, common language, common border, (log) physical distance (e.g. Neumayer 2011; Appelt et al. 2015). In addition to that, the following strategies are used: for specifications that contain country-year policy information, fixed effects are introduced at year and country-pair levels; for specifications that contain cross-sectional barriers, country fixed effects are included to capture country heterogeneity.

The citations data can misrepresent the timing of actual knowledge transfer, which could have taken place at any time prior to the publication.[10] Let t_c represent the time at which a unit of knowledge was generated, t_p is the time of its publication, t_t is when this knowledge was transferred to another researcher, and t_f is the publication time of the citing paper. The knowledge transfer occurs sometime between the conception of the knowledge and the publication of the citing paper, $t_c \leq t_t \leq t_f$, however the only dates that can be observed are t_p and t_f. This introduces a measurement error in the dependent variable (flow of citations from the citing to the cited country), reducing efficiency without biasing the estimates. Moreover, by assigning a publication to countries of author affiliations at the time of publication implicitly assumes localisation of knowledge. At the time of knowledge transfer, the authors of the cited publication could be in a different location. There can also be errors in measurement of the stock of knowledge in the cited country and absorptive capacity in the citing countries at the time of knowledge transfer. However, stock of knowledge in a given country is highly cor-

[10]The discussion in this paragraph is based on a constructive comment by an anonymous referee.

related over adjacent time periods, and the same is true for absorptive capacity, which reduces the potential attenuation bias. If we assume that t_p is close to t_c, then we can reduce any spurious correlations (due to mismeasurement of t_t) by looking at citations within the first few years of t_p.

Finally, if estimations use only non-zero flows, then the estimates will be biased since the sample of countries with non-zero flows is not randomly selected. This is of a particular concern since the median bilateral knowledge flow is 0. To address this concern the equations are estimated using Poisson models on the full, rectangularised dataset with zero values of bilateral knowledge flows.

There are two independent sources of data on administrative barriers to mobility, which will lead to two versions of the estimated equation.

Immigration policy over time

The main specification will use country-year information on migration policy towards skilled workers and students from DEMIG POLICY dataset. The country-year variation in barriers allows including dyad-specific fixed effects as a control for country-pair specific factors. This means that cost variable, $C_{ij,t}$, will include the administrative barriers as follows: $\log C_{ij,t} = P_{i,t} + P_{j,t} + X_{ij} + Z_t$, where $P_{i,t}$ and $P_{j,t}$ are country-specific indexes of immigration policy towards skilled workers and students, while X_{ij} and Z_t are country-pair and time fixed effects, respectively. The equation estimated with this data is:

$$F_{ij,t} = exp(\alpha \log A_{i,t} + \kappa \log K_{j,t} + \beta_1 P_{i,t} + \beta_2 P_{j,t} + X_{ij} + Z_t + \epsilon_{ij,t}),$$

where the negative signs on the cost arguments have been absorbed into the coefficients for convenience.

Cross-sectional data on bilateral visa requirements

The second specification will use country-pair variation in visa requirements, due to limitation of the data the country-pair visa requirement is symmetric (undirected). For consistency, information on knowledge flows is collapsed to (symmetric) country-pair level using information on years 2005–2008 (same time period as in Neumayer 2011). The cost factor in this specification becomes: $\log C_{ij} = V_{ij}^{one} + V_{ij}^{both} + X_{ij} + Y_i + Y j$, where V_{ij}^{one} is a dummy equal to one if one country in a pair imposes a visa restriction (but not both), while V_{ij}^{both} is a dummy equal to one if both countries impose a visa restriction against each other. X_{ij} is a vector containing dyad controls: physical distance, colonial link in the past, common language and border; Y_i,Y_j capture country-specific heterogeneity through fixed effects (dummies).

The equation estimated with this data is:

$$F_{ij} = exp(\beta_1 V_{ij}^{one} + \beta_2 V_{ij}^{both} + \beta_3 X_{ij} + Y_i + Y_j + \epsilon_{ij}). \quad (3)$$

The hypothesis tested in the following section is that the administrative barriers to mobility will have a negative impact on bilateral knowledge flows. Significant estimates of a negative effect of barriers will be consistent with the hypothesis. If the hypothesis is not correct, then the estimated coefficients on the barriers to mobility will be insignificant. In line with the literature, it is expected that the physical distance will have negative effect, while colonial history, common language or border will have a positive effect because they will correlate with social proximity. The results and robustness checks are presented in the next section.

5 Results

5.1 The effect of immigration policies on diffusion of knowledge

The results support the negative role of administrative barriers to mobility in affecting the magnitude and direction of the knowledge flows. Table 4 shows that greater administrative barriers towards skilled workers and students reduce the volume of both incoming and outgoing knowledge flows, the coefficients on barriers are negative for both the citing and the cited countries. The average marginal effect of a moderate increase in barriers (refer to Table 2) is a reduction in the bilateral knowledge flows by about 0.6–1 citations per year (the index changes by 0.5 for a moderate increase in barriers), which corresponds to a 0.8–1.3% decrease in knowledge flows per year (see Table A.1). The coefficients on the barriers in the cited and citing countries are not significantly different from each other, although policy asymmetry shows up in the next specification.

Table 4: The effect of immigration policy on knowledge flows.

	Bilateral citation count		
Barriers for skilled workers and students (cited country)	-1.711	-1.889	
	(0.710)**	(0.778)**	
Barriers for skilled workers and students (citing country)	-1.247	-1.237	
	(0.441)***	(0.443)***	
Stock of publications in the cited country (log)	52.989	58.048	59.839
	(7.503)***	(3.251)***	(3.183)***
New publications in the citing country (log)	61.074	64.507	65.470
	(8.411)***	(3.976)***	(3.456)***
Former colony (of the cited country)		-8.373	-8.160
		(10.093)	(9.931)
Common language		5.159	5.321
		(2.408)**	(2.402)**
Common border		1.679	1.750
		(1.694)	(1.685)
Physical distance (log)		-10.968	-10.887
		(1.033)***	(1.025)***
N	34,742	33,825	33,825
Fixed effects (dummies)			
Cited country	No	Yes	Yes
Citing country	No	Yes	Yes
Dyad	Yes	No	No
Year	Yes	Yes	Yes
p value of the barrier equality	0.58	0.25	-

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: this table shows the average marginal effects, for coefficients see Table A.1; the dependent variable is the aggregate citation count per year (from the citing to the cited country); estimation procedure is 'xtpoisson, fe' with robust standard errors in the first column and Poisson with standard errors clustered at dyad level in the other columns; the results are qualitatively similar if the United States or European Union countries are dropped from the sample.

Diffusion of recent knowledge

The argument put forward in this paper is that effective diffusion of knowledge is enhanced by face-to-face contacts. If this is the case, then the effect of paper walls should be the strongest for diffusion of recent knowledge, which might have a greater tacit component. Using information on the year in which an article was published and the year of the citing article it is possible to decompose the aggregate citation count by 'vintage' or age of citations. This allows to check the effect of administrative barriers on recent knowledge flows, i.e. for articles that are at most Y years old.

Table 5 shows that the largest effect of barriers is observed for $Y = 1$, i.e. for recent knowledge. As Y increases, the impact of immigration policy in the knowledge-exporting country diminishes, but remains relatively more important than the policy of knowledge-importing country. In fact, policy in the knowledge-importing country becomes significant only for $Y \geq 2$. This asymmetry in the role of immigration policies at the origin and destination disappears as Y increases, which is consistent with the argument that colocation at the source of knowledge is important for diffusion of knowledge. An alternative interpretation of these results is that the dependent variable reflects speed of knowledge diffusion, so having lower immigration barriers increases the speed with which a country's knowledge is diffused.

Table 5: The diffusion of recent knowledge and the role of immigration policy.

	Bilateral citation count within Y years			
	All	1	5	10
Barriers for skilled workers and students (cited country)	-0.026	-0.058	-0.046	-0.034
	(0.010)**	(0.013)***	(0.011)***	(0.011)***
Barriers for skilled workers and students (citing country)	-0.019	-0.015	-0.020	-0.020
	(0.007)***	(0.010)	(0.007)***	(0.007)***
N	34,742	34,742	34,742	34,742
Fixed effects				
Dyad	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
p value of the barrier equality test	0.58	0.00	0.06	0.31

Notes: the dependent variable is aggregate citation count per year (from the citing to the cited country) within Y years of publication; estimation procedure is fixed effects Poisson model with robust standard errors; the full table can be found in the appendix, see Table A.3.

A placebo test using future policy

It is possible to test a causal link from immigration policy to knowledge flows by including placebo treatment in the form of leading (future) policy. If the relationship between immigration policy and knowledge flows is causal, then leading barriers should have no effect on knowledge flows. Table 6 shows that the estimates pass this placebo test, providing further support in favour of a causal link from policy to knowledge flows.

Table 6: A placebo test using leading changes in the immigration policy.

	Count of citations from citing to cited Impact of policy Y years in the future			
	1	2	3	5
Leading barriers for high-skilled and students, cited country	-0.007 (0.012)	-0.011 (0.013)	-0.015 (0.013)	-0.010 (0.013)
Leading barriers for high-skilled and students, citing country	-0.009 (0.010)	-0.011 (0.012)	-0.011 (0.013)	-0.012 (0.013)
N	29,470	29,187	28,378	24,887
Dyad FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: the dependent variable is the aggregate citation count per year (from the citing to the cited country), estimation procedure is fixed effects Poisson with robust standard errors; see Table A.5 in the appendix for the full table listing leading policy from 1 to 10 years.

5.2 Robustness

The omitted variable bias and sample selection were addressed in the main results by the appropriate choice of covariates (including fixed effects) and the estimation technique (Poisson with robust standard errors). However, it is possible that some variable contemporaneously affects the knowledge flows and migration policy. To address this concern, the equations were estimated using lagged values of the immigration policies in the cited and citing countries. The results presented in Table 7 show that the coefficients on lagged values of the barriers are significant and the significance of cited country's immigration policy persists for about 9 years. The asymmetry that appeared in specifications with the recent knowledge also shows up here — policy of the knowledge-exporting country remains persistent, while that of the knowledge-importing country is rather short-lived. This provides additional evidence in favour of colocation in the knowledge exporting country being particularly important for diffusion of knowledge.

One dyad-specific variable that can influence bilateral knowledge flows is presence of skilled migrant networks. If colocation is not important for knowledge diffusion, then a larger research community abroad can mitigate the effects of a

Table 7: The persistence of changes in the immigration policy.

	Count of citations from citing to cited Impact of policy implemented Y years ago			
	1	5	9	10
Lagged barriers for high-skilled and students, cited country	-0.015 (0.004)***	-0.018 (0.006)***	-0.017 (0.008)**	-0.009 (0.009)
Lagged barriers for high-skilled and students, citing country	-0.010 (0.004)**	0.002 (0.006)	0.007 (0.006)	0.009 (0.007)
N	33,746	33,337	32,774	32,637
Dyad FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Note: the dependent variable is the aggregate citation count per year (from the citing to the cited country), estimation procedure is fixed effects Poisson with robust standard errors; immigration policy of the cited country remains significant for 9 years, while policy of the citing country loses significance after 2 years; see Table A.4 in the appendix for the full table listing lags from 1 to 10 years.

more strict immigration policy in the cited country. Brücker et al. (2013) provide information on bilateral migrant stocks (by country of birth) for 20 OECD countries, distinguishing levels of migrant's education. This information was used to create bilateral stocks of migrants with tertiary education (high-skilled migrants) in 2005. Table 8 shows the results after adding bilateral stocks of high-skilled migrants.

Including information on bilateral stocks of high-skilled migrants does not alter the magnitude of barrier coefficients, with a marginal reduction in significance barriers in the cited country. Controlling for highly-skilled migrants removes significance of common language and reduces the negative role of distance. It's possible that lower barriers leads to a turnover in migrant stocks (which is not captured in the bilateral stock measure), with new cohorts facilitating transfer of knowledge.

A drawback of the data used in main results is that it makes use of country-specific policies. Information on travel visa requirements will capture dyad-specific barriers to high-frequency (or short-term) mobility. If colocation is important, then visa barriers should have a negative effect on bilateral knowledge flows. Table 9 shows that countries with mutual visa restrictions have significantly lower average (undirected) bilateral knowledge flows. This finding is robust to different estimation procedures (Poisson, PPML, OLS). The estimated effect is much larger than that of immigration policy, with bilateral visa restriction reducing average knowledge flows by about 18%.

The coefficient on past (symmetric) colonial link was expected to be positive, but colonial ties appear to have a negative effect on average (undirected) knowledge

Table 8: The role of bilateral high-skilled migrant networks.

	Bilateral citation count		
Barriers for skilled workers and students (cited country)	-0.019 (0.009)**	-0.019 (0.010)**	-0.019 (0.010)*
Barriers for skilled workers and students (citing country)	-0.018 (0.007)***	-0.018 (0.007)**	-0.019 (0.007)***
Stock of publications in the cited country (log)	0.905 (0.043)***	0.876 (0.049)***	0.881 (0.049)***
New publications in the citing country (log)	0.904 (0.042)***	0.885 (0.050)***	0.886 (0.049)***
Former colony (of the cited country)		-0.144 (0.146)	-0.157 (0.118)
Common language		0.091 (0.032)***	0.044 (0.029)
Common border		0.056 (0.022)***	0.053 (0.018)***
Physical distance (log)		-0.136 (0.013)***	-0.109 (0.012)***
Bilateral stock of high-skilled migrants (log)			0.066 (0.012)***
N	17,393	17,393	17,393
Fixed effects (dummies)			
Cited country	No	Yes	Yes
Citing country	No	Yes	Yes
Dyad	Yes	No	No
Year	Yes	Yes	Yes
p value of the barrier equality	0.92	0.90	0.94

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: the dependent variable is the aggregate citation count (from the citing to the cited country); estimation procedure is fixed effects Poisson with robust standard errors in the first column and Poisson with standard errors clustered at dyad level in the other columns; data on bilateral stocks of migrants with high education come from Brücker et al. (2013).

Table 9: The effect of visa requirements on average bilateral knowledge flows.

	Average bilateral citation count		
	level	level	log
Visa restriction for both countries	-0.267	-0.176	-0.664
	(0.086)***	(0.075)**	(0.075)***
Visa restriction by one country only	0.049	0.039	-0.655
	(0.053)	(0.041)	(0.052)***
Colonial link in the past		-0.146	-0.290
		(0.076)*	(0.126)**
Common language		0.077	0.011
		(0.051)	(0.070)
Common border		-0.015	0.073
		(0.032)	(0.081)
Physical distance (log)		-0.167	-0.419
		(0.023)***	(0.029)***
N	13,027	12,475	3,093
Fixed effects (dummies)			
Cited country	Yes	Yes	Yes
Citing country	Yes	Yes	Yes

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: the dependent variable is the absolute value or logarithm of the average bilateral (undirected) citation count between a pair of countries over 2005–2008 time period; right-hand side variables are from year 2004 or the closest available year (data from (Neumayer 2011)); estimation procedure is PPML in the first two columns and OLS, with robust standard errors in all columns; the results are qualitatively similar if the United States or European Union countries are dropped from the sample.

flows. A directed colonial ties variable was not significant in the main specifications, so it's possible that the significance of the colonial variable in Table 9 might be driven by the symmetry in the data used in estimation. The symmetric colonial link variable is equal to 1 for pairs that typically represent a developing (former colony) and a developed country, compared to 0 for all other pairs (including developing countries without a colonial history). The symmetry doesn't allow further exploration of the negative coefficient and it's possible that it is influenced by an unmeasured aspect of development (former colonies, on average, are less advanced scientifically).

6 Discussion and conclusion

The results obtained using three independent sources of data (Web of Science, DEMIG POLICY and IATA) suggest that the administrative barriers to mobility are associated with reduced bilateral knowledge flows. This effect is strongest for flows of recent knowledge, and policy of the knowledge-exporting country appears to be more important (in terms of short-term magnitude and persistence) relative to knowledge-importer's policy. This asymmetry is consistent with the hypothesis that administrative barriers to mobility limit transfer of knowledge via personal, face-to-face contacts. The reduction in knowledge flows in both directions implies that incoming and outgoing researchers are important for diffusion of knowledge. Such circular mobility also contributes to turnover in the stock of bilateral migrant researchers, expanding access to the knowledge embedded in the 'weak ties' of domestic and foreign researchers' networks. The results are robust to changes in specifications and are observed with independent measures of the administrative barriers to mobility. The placebo test based on the leading values of the immigration policy does not reject a causal link from the administrative barriers to knowledge flows.

The reduction in knowledge flows associated with a moderate increase in barriers is 0.8-1.3% per year, which might appear innocuous in the short-term. However, it can have an important long-term effect on the direction of research. Such diversion effects are not addressed in this paper, but could explain the loss of significance of immigration policy after about 10 years. The barriers between two countries could lead to increase in their bilateral cognitive distance over time, resulting in a decrease of knowledge flows over time. Furthermore, a decline in knowledge flows eventually can affect the productivity and innovations in the industry.[11]

[11]This claim might be too strong given that knowledge flows in this paper were calculated for citations among economists. As long as the geographic pattern of knowledge flows in Economics is representative of the flows in other areas of science, especially those more directly applicable to engineering and manufacturing, then the effects identified in this paper are likely to lead to

Focus on the aggregate flows does not allow distinguishing qualities of the cited and citing articles. It might be expected, for example, that publications with wider applicability will diffuse more rapidly and farther, despite any administrative barriers to the mobility of the authors. A possible way to examine this effect is to use micro-level (publication) data, which will allow introducing additional controls at the paper-level (e.g. Iaria and Waldinger 2015; Head et al. 2015).

Observing gravity in knowledge flows is not a novel result and is intuitive given that gravity framework explains a wide range of social processes. The contribution of this paper is to show that the administrative barriers to mobility can have a significant and persistent effect on the direction and magnitude of international knowledge flows. The evidence obtained from the paper trails left by knowledge flows suggests that, though weightless, knowledge flows can be deflected by the paper walls.

Establishing causality from observational data is notoriously difficult, so translation of the results to policy implications must be done with caution and consideration of policy-specific context. However, it appears that achieving faster convergence to the frontier of knowledge requires lowering of immigration barriers not just in the knowledge-importing countries (developing), but also in the knowledge-exporting (developed) countries. Paper walls are man-made and can be torn down (McKenzie 2007). The link between mobility barriers and knowledge flows must be considered in formulation of immigration and development policies. Research funding programs can also encourage international mobility, both low- and high-frequency, to facilitate diffusion of knowledge.

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A Appendix: Additional tables

Table A.1: The effect of immigration policy on knowledge flows.

	Bilateral citation count		
Barriers for skilled workers and students (cited country)	-0.026	-0.027	
	(0.010)**	(0.011)**	
Barriers for skilled workers and students (citing country)	-0.019	-0.017	
	(0.007)***	(0.006)***	
Stock of publications in the cited country (log)	0.814	0.820	0.845
	(0.042)***	(0.046)***	(0.045)***
New publications in the citing country (log)	0.938	0.911	0.925
	(0.035)***	(0.056)***	(0.048)***
Former colony (of the cited country)		-0.118	-0.115
		(0.142)	(0.140)
Common language		0.073	0.075
		(0.034)**	(0.034)**
Common border		0.024	0.025
		(0.024)	(0.024)
Physical distance (log)		-0.155	-0.154
		(0.014)***	(0.014)***
N	34,742	33,825	33,825
Fixed effects (dummies)			
Cited country	No	Yes	Yes
Citing country	No	Yes	Yes
Dyad	Yes	No	No
Year	Yes	Yes	Yes
p value of the barrier equality	0.58	0.25	-

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: this table shows the estimated coefficients for regressions in which the dependent variable is the aggregate citation count per year (from the citing to the cited country); estimation procedure is 'xtpoisson, fe' with robust standard errors in the first column and Poisson with standard errors clustered at dyad level in the other columns; the results are qualitatively similar if the United States or European Union countries are dropped from the sample.

Table A.2: The effect of immigration policy on (log) knowledge flows.

	Bilateral citation count		
Barriers for skilled workers and students (cited country)	-0.119	-0.131	
	(0.009)***	(0.012)***	
Barriers for skilled workers and students (citing country)	-0.066	-0.067	
	(0.009)***	(0.011)***	
Stock of publications in the cited country (log)	0.690	0.369	0.391
	(0.015)***	(0.036)***	(0.037)***
New publications in the citing country (log)	0.702	0.595	0.604
	(0.016)***	(0.034)***	(0.035)***
Former colony (of the cited country)		0.061	0.071
		(0.091)	(0.088)
Common language		0.186	0.181
		(0.049)***	(0.049)***
Common border		0.147	0.142
		(0.047)***	(0.047)***
Physical distance (log)		-0.212	-0.214
		(0.021)***	(0.021)***
N	20,715	19,911	19,911
Fixed effects (dummies)			
Cited country	No	Yes	Yes
Citing country	No	Yes	Yes
Dyad	Yes	No	No
Year	Yes	Yes	Yes
p value of the barrier equality	0.00	0.00	-

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: the dependent variable is the log of aggregate citation count per year (from the citing to the cited country); estimation procedure is 'xtreg, fe' with robust standard errors in the first column and OLS with standard errors clustered at dyad level in the other columns; the results are qualitatively similar if the United States and European Union countries are dropped from the sample.

Table A.3: The diffusion of recent knowledge and the role of immigration policy.

	Bilateral citation count within Y years										
	All	1	2	3	4	5	6	7	8	9	10
Barriers for skilled workers and students (cited country)	-0.026	-0.058	-0.054	-0.050	-0.045	-0.046	-0.044	-0.042	-0.039	-0.037	-0.034
	(0.010)**	(0.013)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***	(0.011)***
Barriers for skilled workers and students (citing country)	-0.019	-0.015	-0.016	-0.016	-0.018	-0.020	-0.020	-0.020	-0.021	-0.020	-0.020
	(0.007)***	(0.010)	(0.008)*	(0.008)**	(0.007)**	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***
Stock of publications in the cited country (log)	0.814	0.671	0.675	0.697	0.716	0.735	0.748	0.762	0.774	0.785	0.797
	(0.042)***	(0.104)***	(0.073)***	(0.061)***	(0.054)***	(0.051)***	(0.049)***	(0.048)***	(0.047)***	(0.047)***	(0.046)***
New publications in the citing country (log)	0.938	0.913	0.911	0.911	0.914	0.915	0.916	0.922	0.928	0.932	0.934
	(0.035)***	(0.053)***	(0.046)***	(0.044)***	(0.043)***	(0.043)***	(0.044)***	(0.043)***	(0.042)***	(0.041)***	(0.041)***
N	34,742	34,742	34,742	34,742	34,742	34,742	34,742	34,742	34,742	34,742	34,742
Fixed effects											
Dyad	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
p value of the barrier equality test	0.58	0.00	0.01	0.01	0.05	0.06	0.09	0.11	0.17	0.23	0.31

Notes: the dependent variable is aggregate citation count per year (from the citing to the cited country) within Y years of publication; estimation procedure is fixed effects Poisson model with robust standard errors.

Table A.4: The persistence of changes in the immigration policy (xtpoisson).

	Count of citations from citing to cited Impact of policy implemented Y years ago										
	0	1	2	3	4	5	6	7	8	9	10
Stock of papers in the cited country	0.807	0.806	0.807	0.807	0.808	0.810	0.811	0.813	0.816	0.816	0.814
	(0.040)***	(0.040)***	(0.040)***	(0.040)***	(0.040)***	(0.040)***	(0.040)***	(0.041)***	(0.041)***	(0.041)***	(0.041)***
New papers in the citing country	0.941	0.941	0.941	0.942	0.942	0.940	0.941	0.940	0.940	0.935	0.931
	(0.036)***	(0.036)***	(0.036)***	(0.036)***	(0.036)***	(0.036)***	(0.036)***	(0.037)***	(0.037)***	(0.038)***	(0.038)***
Barriers for high-skilled and students, cited country	-0.027	-0.014	-0.017	-0.019	-0.021	-0.025	-0.027	-0.030	-0.031	-0.031	-0.028
	(0.010)**	(0.011)	(0.011)	(0.011)*	(0.011)**	(0.010)**	(0.010)***	(0.010)***	(0.010)***	(0.010)***	(0.010)***
Barriers for high-skilled and students, citing country	-0.019	-0.010	-0.017	-0.017	-0.018	-0.019	-0.019	-0.019	-0.019	-0.018	-0.018
	(0.007)***	(0.007)	(0.007)**	(0.008)**	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***
Lagged barriers for high-skilled and students, cited country		-0.015	-0.013	-0.015	-0.019	-0.018	-0.021	-0.024	-0.022	-0.017	-0.009
		(0.004)***	(0.005)***	(0.005)***	(0.006)***	(0.006)***	(0.007)***	(0.007)***	(0.007)***	(0.008)**	(0.009)
Lagged barriers for high-skilled and students, citing country		-0.010	-0.003	-0.005	-0.003	0.002	-0.000	0.001	0.002	0.007	0.009
		(0.004)**	(0.005)	(0.007)	(0.007)	(0.006)	(0.007)	(0.006)	(0.006)	(0.006)	(0.007)
N	33,746	33,746	33,678	33,540	33,475	33,337	33,184	33,048	32,911	32,774	32,637
Dyad FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: the dependent variable is the aggregate citation count per year (from the citing to the cited country), estimation procedure is 'xtpoisson, fe' with robust standard errors; estimation using PPML yields the same results.

Table A.5: A placebo test using leading changes in the immigration policy (xtpoisson).

	Count of citations from citing to cited Impact of policy Y years in the future										
	0	1	2	3	4	5	6	7	8	9	10
Stock of papers in the cited country	0.807	0.789	0.786	0.783	0.781	0.796	0.810	0.831	0.819	0.819	0.829
	(0.040)***	(0.046)***	(0.046)***	(0.048)***	(0.052)***	(0.052)***	(0.049)***	(0.044)***	(0.046)***	(0.049)***	(0.055)***
New papers in the citing country	0.941	0.913	0.910	0.909	0.903	0.900	0.907	0.913	0.914	0.917	0.912
	(0.036)***	(0.040)***	(0.041)***	(0.042)***	(0.044)***	(0.042)***	(0.036)***	(0.028)***	(0.025)***	(0.024)***	(0.027)***
Barriers for high-skilled and students, cited country	-0.027	-0.011	-0.009	-0.007	-0.011	-0.011	-0.014	-0.018	-0.023	-0.016	-0.012
	(0.010)**	(0.007)	(0.006)	(0.005)	(0.006)*	(0.008)	(0.011)	(0.016)	(0.016)	(0.015)	(0.015)
Barriers for high-skilled and students, citing country	-0.019	-0.006	-0.005	-0.007	-0.008	-0.009	-0.007	-0.016	-0.016	-0.015	-0.010
	(0.007)***	(0.007)	(0.007)	(0.007)	(0.006)	(0.007)	(0.008)	(0.015)	(0.017)	(0.017)	(0.016)
Leading barriers for high-skilled and students, cited country		-0.007	-0.011	-0.015	-0.011	-0.010	-0.006	-0.007	-0.010	-0.007	-0.015
		(0.012)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.016)	(0.019)
Leading barriers for high-skilled and students, citing country		-0.009	-0.011	-0.011	-0.012	-0.012	-0.003	-0.007	-0.004	-0.004	-0.001
		(0.010)	(0.012)	(0.013)	(0.013)	(0.013)	(0.013)	(0.012)	(0.013)	(0.011)	(0.009)
N	33,746	29,470	29,187	28,378	26,738	24,887	23,118	21,216	19,381	17,477	15,661
Dyad FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Notes: the dependent variable is the aggregate citation count per year (from the citing to the cited country), estimation procedure is 'xtpoisson, fe' with robust standard errors; estimation using PPML yields the same results.