IMF Working Paper

Why U.S. Immigration Matters for the Global Advancement of Science

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INTERNATIONAL MONETARY FUND

IMF Working Paper

Asia and Pacific Department

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Authorized for distribution by Alfred Schipke

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Why U.S. Immigration Matters for
the Global Advancement of Science[*]

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Abstract

This paper studies the impact of U.S. immigration barriers on global knowledge production. We present four key findings. First, among Nobel Prize winners and Fields Medalists, migrants to the U.S. play a central role in the global knowledge network—representing 20-33% of the frontier knowledge producers. Second, using novel survey data and hand-curated life-histories of International Math Olympiad (IMO) medalists, we show that migrants to the U.S. are up to six times more productive than migrants to other countries—even after accounting for talent during one's teenage years. Third, financing costs are a key factor preventing foreign talent from migrating abroad to pursue their dream careers, particularly for talent from developing countries. Fourth, certain 'push' incentives that reduce immigration barriers – by addressing financing constraints for top foreign talent – could increase the global scientific output of future cohorts by 42 percent. We conclude by discussing policy options for the U.S. and the global scientific community.

I. Introduction

While talent can be born anywhere, few places specialize in nurturing it. Accordingly, talented individuals have pursued opportunities abroad for centuries. For instance, Aristotle moved from Northern Greece to Athens to attend Plato's Academy, and then to Macedonia to tutor a young Alexander the Great. More recently, the U.S. has emerged as a hub for foreign talent, playing an outsized role in the global knowledge network of scientific activity in recent decades. However, the recent introduction of restrictive immigration policies in the U.S. may adversely impact scientific activity. While studies have examined the potential adverse impact of restrictive U.S. immigration policies on *U.S.* competitiveness in science and innovation (e.g. Lowe 2020), there has been less focus on understanding how U.S. immigration barriers may in turn impact scientific activity globally. In this context, this paper studies the impact of U.S. immigration barriers on global knowledge production, and examines which policy actions are more likely to help advance the global knowledge frontier.

The quantitative impact of immigration barriers on global science and on worldwide cross-border flows remains an under-studied question, mainly due to the difficulty of collecting and linking data on migration and scientific production on a global scale. Yet, examining the impact of U.S. immigration barriers on the global advancement of science appears both essential and timely—especially given the potentially large consequences of immigration flows for global innovative activity.[1] Individuals from developing countries who show similar talent as youth from advanced countries are less able to contribute to advancing the global knowledge frontier during their lifetime, suggesting large scientific gains can be achieved by easing barriers for their

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[1] Scientific activity is increasingly organized to take advantage of international collaboration, with a heavy reliance on cross-border flow of ideas and people (Kerr 2008; Freeman, Ganguli, Murciano-Goroff 2015; Scellato, Franzoni & Stephan 2015; Bahar, Choudhury & Rapoport 2020).

migration to places where their talent can be nurtured (Agarwal & Gaule 2020). Moreover, recent developments—the COVID-19 pandemic and changes in U.S. immigration policy—have created further barriers for cross-border migration and may significantly disrupt the current equilibrium. For instance, student visas (F1) to the U.S. fell by 70 percent between fiscal years 2019 and 2020.[2] Many of the immigrants who can no longer come to the U.S. to work and study due to recent immigration and travel barriers represent a substantial share of the most talented individuals from around the globe.

Our contribution is to quantify how U.S. immigration barriers could impact the advancement of science using hand-curated datasets of talented individuals – Nobel laureates, Fields medalists, and participants of the International Math Olympiads (IMO), a prominent worldwide math competition for talented high school students. Our dataset includes career histories of migration and lifetime scientific output of 2,200 IMO medalists from over one hundred countries. We combine these data with newly collected unique survey data of 610 recent IMO participants, which includes information on which universities they applied to, were admitted to and attended. The survey also asks a series of questions where respondents were asked to make choices between hypothetical university offers in different countries—where offers were either funded or unfunded. In line with recent work emphasizing the use of such conjoint survey experiments (Hainmueller, Hangartner & Yamamoto 2015), these questions allow us to shed light on the role of funding as a constraint to pursuing education abroad.

We present four main findings. First, using data on Nobel Prize winners and Fields Medalists, we document that the migrants to the U.S. play a central role in the global knowledge

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[2] Further, on September 25th, 2020, the Department of Homeland Security proposed a rule to end the 'duration of status' on visas for foreign students, exchange visitors (and journalists), which would make it much harder and expensive for this group to study in the U.S.

network— representing 20-33% of these frontier knowledge producers. Second, using novel survey data and hand-curated life-histories of International Math Olympiad (IMO) medalists, we show that migrants to the U.S. are significantly more productive than migrants to other countries— even after accounting for one's talent during their teenage years. Migrants to the U.S. are *four* to *six* times more productive than stayers, while migrants to the U.K. are more than *twice* as productive as stayers. Using information on the future occupations of the medalists we show that the U.S. productivity premium is driven by both the extensive margin (i.e. migrants are more likely to choose academic careers when they migrate to the U.S.), and the intensive margin (i.e. among those who choose academic careers in math, migrants to the U.S. are more productive than stayers).

Third, we document that financing costs are a key factor preventing foreign talent to migrate to the U.S. In particular, among developing country IMO participants, 66% dream of studying in the U.S. while only 25% manage to do so. Fourth, our findings suggest that certain 'push' incentives that reduce immigration barriers to the U.S.—by addressing financing constraints for top foreign talent—could increase the global scientific output of future cohorts of talent by 42% percent. We conclude by discussing policy options for the U.S. and the global scientific community, with a particular focus on the effectiveness of scholarships vs. other science policy actions such as offering green cards to foreign talent.

II. Data

II. a. IMO Medalists, Fields Medalists and Nobel Laureates

IMO medalists database. We extracted data on all IMO participants from the official IMO website (http://www.imo-official.org) and selected the subset who (a) participated between 1981 and 2000, and (b) received a medal. We focus on cohorts in the 1980s and 1990s because for them we can observe at least two decades post-participation, and hence a sizeable number of years after

the PhD. We consider the country an IMO medalist represented at the IMO to be his/her origin country. Participants' occupations and current country of residence were manually collected using Google, LinkedIn and similar sources.[3] We classify occupations into four categories: math academia, non-math academia, information technology (IT) and finance.[4] We also classify IMO medalists as migrants if the country they represented at the IMO was different from the country they were working in as of 2016 (with their place of work determined by manual data collection). We further classify them into migrants to the U.S. if they did not represent the U.S. at the IMO and their place of work in 2016 was in the U.S. Finally, we measure the scientific productivity of IMO medalists in two ways. First, we use mathematics publications weighted by cites as per the MathSciNet public author pages.[5] Second, we use a measure of community recognition independent of bibliometrics: being invited to speak at the International Congress of Mathematicians (ICM), a prestigious accomplishment for mathematicians.

Nobel laureates and Fields Medalists database. We measure the production of frontier knowledge through the receipt of a Nobel laureate of a Fields medal in mathematics. Either of these prizes is extremely prestigious and features in the Shanghai ranking of world universities. The data on Nobel laureates was extracted from the official Nobel Prize website (https://www.nobelprize.org/). Similarly, the names of Fields medalists were taken from International Mathematical Union (https://www.mathunion.org/imu-awards/fields-medal). For the Nobel laureates, we selected individuals who received the award in Chemistry, Physics and

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[3] For 55% of IMO medalists in our sample, we were able to find their current (as of 2016) employment and location. For people whom we could not trace, they stay in the sample and we assume that they are still living in their origin country. Note that we since we do not distinguish between return migrants from those who always stayed in their origin country, we may miss temporary migration spells. For these reasons, our migration estimates based on the observational data should be seen as a lower bound on migration.

[4] Academics tend to be highly visible online, while industry employment is observed with less precision. A substantial (45%) share of our sample cannot be matched to any occupation.

[5] MathSciNet is a service of the American Mathematical Society with extensive coverage of publications in mathematics.

Physiology and Medicine since 2000. For the Fields medalists, we selected individuals who received the award since 1990. We classify the Nobel laureates and Fields Medalists as migrants if their country of birth is different from the country of their main academic affiliation at the time of the award. We classify them as migrants to the U.S. if their main academic affiliation at the time of the award was in the U.S. and their country of birth was not the U.S.

II. b. Survey of IMO Participants

The data on IMO medalists described earlier has the advantages of being extensive and include productivity measures over a sizeable share of their careers. However, it contains no information on what individuals did directly after the IMO and the factors that influenced their educational and career decisions. In order to develop a better understanding of the educational and geographic choices of IMO participants, we conducted a retrospective survey of former IMO participants in June 2019.[6] With the help of the Secretary of the IMO Board, we contacted the IMO representatives of all participating countries, asking them to distribute the survey to former IMO participants from their country. Our communication emphasized that we were most interested in responses from recent participants (last 10 years) but also accepted responses from participants from previous cohorts. In order to incentivize participation, we offered five Amazon vouchers worth 80 British pounds (or an equivalent donation to a charity). Additionally, survey recipients had the opportunity to access and solve two new (never published) mathematical problems. We received answers from IMO participants from a broad range of countries (76 countries), although

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[6] The survey was approved by the Social Science Research Ethics Committee at the University of Bath and included a consent form and an information sheet for participants.

IMO representatives from some countries did not distribute the survey, for example since some did not maintain a mailing list of former participants.[7]

We received a total of 610 useable responses. By comparison, there were 5,666 IMO participants from 2009 to 2018. IMO participants who responded to the survey were relatively more likely to have received a medal than IMO participants (55% versus 50%, see Table S1). Participants from Europe, Central Asia, and Latin America and the Caribbean regions were slightly overrepresented among respondents. Conversely, participants from South Asia, and the Middle East and North Africa were relatively underrepresented.

Besides questions on demographics, career preferences, life satisfaction and reasons to participate in the IMO, the survey included an extensive set of questions on decisions about where to study for an undergraduate degree. In particular, we asked respondents about which institutions they considered applying to (up to five and in order of preference) and among those, where they actually applied, where they received admission offers from and which undergraduate institution they actually attended. The survey also asked where the participants would have wanted to study if they could have studied anywhere in the world. We also asked for the importance of different factors for choosing to enroll in their undergraduate institution rather than a different one. Finally, we asked a series of counterfactual choice questions where respondents were asked to choose between counterfactual admission offers to institutions of different ranking and usually in the same country, with one being funded and the other not.

III. Empirical Strategy

III. a. Migrant Productivity Regressions

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[7] Since we did not have emails of former participants, we were unable to send reminders to individual participants, although we did remind IMO country representatives.

In order to estimate the productivity advantage associated with migration, we run the following regressions on the sample of IMO medalists:

$$Productivity_{ijt} = \beta Migrant_i + \eta_i + \zeta_t + \gamma_i + \varepsilon_i \qquad (1)$$

where i indexes medalists, t Olympiad years and j origin countries. $Productivity_{ijt}$ is the number of mathematics publications or cites a medalist has over her career (up until 2017), or an indicator for becoming a speaker at the International Congress of Mathematicians. $Migrant_i$ is an indicator variable for whether we observe that the individual is a migrant, Controls include η_j, a set of fixed effects for the number of points scored by individual i in his/her last IMO participation, ζ_t, a set of fixed effects for the year in which the individual last participated, $\gamma_{i,}$, a set of fixed effects for the country the individual represented at the IMO.

By controlling for IMO score fixed effects, we compare individuals who had the same level of problem-solving ability in their late teens, thus mitigating concerns about endogeneous selection into migration based on early indicators or talent. In the alternative specification, we replace the migrant indicator variable by indicator variables for migrant to the U.S., migrant to the U.K. and migrant to other countries. The regressions are estimated by Poisson (when cites is the dependent variable) or Ordinary Least Squares (when becoming a speaker at the International Congress of Mathematicians).

To examine the extensive vs. intensive margin effects underlying the productivity premium, we also run similar regressions where the dependent variable is (a) the occupation of the medalists for the sample of all medalists, or (b) the productivity measure with the sample restricted to those who choose academic careers in math.

III. b Counterfactual choices questions and regressions

In order to investigate the role of financing in choices between alternative undergraduate degree institutions, we asked a series of hypothetical choice questions. In these questions, respondents choose between two offers for undergraduate admissions. The offers were structured to involve an unfunded offer from a higher ranked institution (according to the Shanghai rankings) and a funded offer from a somewhat lower ranked institution, usually in the same country.[8]

Having set up the counterfactual choice data as a panel at the student and choice (university-pair) level, we run regressions of the type:

$$Preferfunded_{i,jk} = \beta Developing_i + \gamma_{jk} + \varepsilon_{i,jk} \tag{2}$$

Where i indexes students and j and k index the undergraduate institutions in the offer set. $Preferfunded_{i,jk}$ is an indicator variable for choosing the funded option, $Developing_i$ is an indicator variable if the respondent is from a developing country and γ_{jk} is a fixed effect for the choice (university pair). Because we have pair fixed effects, we are effectively asking how a developing country and developing country student would choose when confronted with the exact same choice.

IV. Results

IV. a. Importance of Migrants to the U.S. in the Global Knowledge Network of Science

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[8] Specifically, the choices were as follows:

[Block A] (1) University of Cambridge unfunded versus Imperial College funded, (2) University of Cambridge unfunded versus University of Manchester funded, (3) University of Cambridge unfunded versus University of Edinburgh funded (4) University of Cambridge unfunded versus Swiss Federal Polytechnic School of Lausanne funded.

[Block B] (1) Stanford University unfunded versus New York University funded, (2) Stanford University unfunded versus Carnegie Mellon funded, (3) Stanford University unfunded versus Boston University funded (4) Stanford University unfunded versus Swiss Federal Polytechnic School of Lausanne funded.

To reduce the burden on respondents, respondents received either the Block A or Block B but not both.

This section presents two results: (1) the importance of the U.S. in the global knowledge network, and (2) the importance of foreign talent migrating to the U.S. for the total global frontier knowledge production.

First, we start by examining the migration patterns of Nobel laureates, which provide useful insights into the modern global knowledge network (Li et al. 2019). Figure 1A provides new visualizations of the network of migration patterns of all Nobel laureates in Chemistry, Physics, Physiology and Medicine since 2000. The nodes are the countries of birth and their countries of residence at the time of receiving the prize. The ties connecting them are the migration flows, where thicker lines indicate larger flows. A few high-income countries—the U.S., the U.K., France and Germany—are hubs attracting talent from multiple origin countries, which tend to be middle-income countries. Quantitatively, the importance of the U.S. in the network is central (the in-degree centrality measure for the U.S. is 14). Migrants to the U.S. account for one in five worldwide Nobel Prize Winners in science. These findings are consistent with prior work that has shown that much of the world's top talent migrates to the U.S. (Weinberg 2011, Hunter, Oswald & Charlton 2009, Kerr 2018) but only some eventually return to their countries of origin (Gaule 2014).

Considering Nobel laureates only may induce a survivorship bias, as highly talented individuals who do not make it to the pinnacle of scientific achievement are not in the sample. For instance, in our sample of Nobel laureates, only one was born in a low income or lower middle-income country. To reduce the role of this survivorship bias, we can instead focus on a set of highly talented individuals much earlier as teenagers: medalists of the IMO. Prior work (Agarwal & Gaule 2020) shows that such talented youth are especially capable of advancing the knowledge frontier. For example, an IMO gold medalist is fifty times more likely to win a Fields Medal in math

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compared to other PhD graduates from top 10 mathematics programs. However, while participants from developing countries often excel at the IMO, they are less likely to advance the knowledge frontier than equally talented counterparts from advanced countries.

In figure 1B, we replicate the network graph using data from migration flows of IMO participants who were gold medalists between 1981-2000. The U.S. again appears as a major magnet for talent born elsewhere (in-degree centrality measure for the U.S. is 19), but the origin countries now include many low and lower middle-income countries. The number of medalists living in the U.S. is five times larger than the number of medalists produced by the U.S., a ratio far higher than for any other country (see figure A1).

Next, we quantify the contributions of immigrants—particularly those migrating to the U.S—to the global frontier scientific knowledge. We use the term frontier knowledge to refer to groundbreaking achievements in respective scientific fields. For this exercise, we look at recipients of the Nobel prizes in physics, chemistry and physiology or medicine (2001-2019) and the Fields Medal in mathematics (1990-2018). We find that 21% of Nobel prize winners and 33% of Fields medalists are migrants to the U.S. (see Figure 2). A further 11% of Nobel prize winners, and 30% of Fields medalists are migrants to countries other than the U.S. These results highlight both the important role played by immigrants in the global production of knowledge, and the importance of the U.S. as a migration destination.

IV. b. Are Migrants to the U.S. More Productive than Stayers and Migrants to Other Countries?

The importance of migration barriers for the advancement of science is tightly linked to the effect of migration on scientific productivity at the individual level. If individuals are equally productive irrespective of whether they migrate or not, then migration flows (and hence migration

policy) are bound to have little impact on global knowledge production. However, prior literature shows that talented individuals who come from less favorable environments produce less knowledge (Agarwal & Gaule 2020). Moreover, there is growing evidence that being trained or working in the U.S. may substantially boosts the research productivity of foreign doctoral students (Kahn & MacGarvie 2016) and the productivity or earnings of foreign scientists and engineers—as in the case of Russian émigré scientists after the collapse of Soviet Union, IT workers from India, or high academic achievers from five Pacific countries (Ganguli 2017; Clemens 2013; Gibson & McKenzie 2011; Gibson & McKenzie 2012; Gibson & McKenzie 2014). A similar location premium is observed within the U.S. (Chetty & Hendren 2018; Bell et al. 2019). We would therefore expect that moving to the U.S. leads to an increase in scientific productivity.

To estimate this 'U.S. migration productivity premium', we compare the scientific publications of IMO medalists who stay in their origin country versus those who migrate to the U.S. and those who migrate to other countries. To mitigate concerns about endogenous selection into migration (even within the relatively homogeneous group of IMO medalists), we control for the number of points scored at the IMO. Prior work shows that the IMO score is a strong predictor of future productivity (Agarwal & Gaule 2020). Therefore, our empirical setting allows us to compare future scientific productivity as a function of their migration decisions, among individuals who had the same level of observable talent in teenage years.

We estimate Poisson regressions with mathematics publications (or citation-weighted publications) as outcome variables. We regress publications on indicator variables for being a migrant, being a migrant to the U.S. or a migrant to another country, and we control for country-of-origin fixed effects, year of IMO participation fixed effects and IMO score fixed effects (total

points received at the IMO competition). The coefficient on migrant provides an estimate of the productivity advantage of those who migrate compared to those who stay in their origin country.

We find that migrants are approximately three times more productive than stayers in terms of citation-weighted publications (see Table 1 column 1).[9] Distinguishing between migrants to the U.S., migrants to the U.K. (the second largest destination) and migrants to other countries, we find that migrants to the U.S. are *four* times more productive than stayers (in terms of citation-weighted publications) while migrants to the U.K. or to other countries are only around *twice* as productive as stayers (Table 1 Column 2).

In columns 3 and 4, we consider becoming a speaker at the International Congress of Mathematicians (ICM) – a prestigious community recognition – as the dependent variable. Migrants are four times more likely than stayers to become ICM speakers (Table 1 Column 3). However, when we distinguish between destination countries, migrants to the U.S. are *six* times more likely than stayers to become ICM speakers while the point estimate for migrants to the U.K. and to other countries is small and not significantly different from zero.

Taken together, these results suggest that migration to the U.S. is associated with a considerably greater productivity premium than migration to other advanced countries.

IV. c. What Explains the Migration Productivity Premium?

In this section, we examine why IMO medalists who migrate abroad (especially to the U.S.) have more productive research careers in mathematics. We distinguish between two effects: the 'extensive' margin vs. 'intensive' margin. That is, the productivity premium may be due (a) to migrants being relatively more likely to choose academic careers in math (the

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[9] Given that we use a Poisson regressions, a coefficient of 1.445 implies a relative effect of exp(1.445)-1 ≈3.2

extensive margin), or (b) among those who choose academic careers in math, migrants are more productive than stayers (the intensive margin).

Table 2 presents the extensive margin results. These regressions estimate the future career choices of IMO medalists as a function of whether they later migrated abroad. Compared to stayers, migrants are at least twice as likely as stayers to be employed in math academia as well as in academic careers academia. They were also more likely to be employed in finance or IT. Distinguishing between migrants to the U.S., migrants to the U.K. (the second largest destination), and migrants to other countries, we find similar excess propensity of migrants to enter academic careers in math or non-math in the U.S., U.K. or other migration destination (Table 2 Panel B columns 1 and 2) compared to stayers. However, considering non-academic occupations, we find that IMO medalists who move to the U.S. are the most likely to enter IT occupations compared to stayers, while those who move to the U.K are the most likely to enter finance occupations (Table 2 Panel B columns 3 and 4).

Table 3 presents the intensive margin results. These regressions are identical to the specifications in Table 1, except here we restrict the sample to those IMO medalists that eventually entered academic careers in math. Migrants tend to be considerably more productive (and more likely to be become speakers at the International Congress of Mathematicians) than stayers. However, closer examination suggests that while migrants to the U.S. are 2.5 more productive than stayers, there is no productivity difference between migrants to the U.K. and stayers.

Taken together, these results suggest that the extensive and intensive margins play a broadly similar role in explaining the productivity premium in mathematics research between migrants to the U.S. and stayers. On the other hand, the productivity premium between migrants

to the U.K. and stayers can be entirely explained by the extensive margin. The presence of little to no intensive margin effects for migrants to the U.K. or other non-U.S. destinations may also explain why migrating to the U.S. is associated with a relatively larger productivity premium.

IV. d. American Dream vs. Reality: Immigration Barriers for Foreign Talent

Understanding how immigration barriers impact the global knowledge network of scientific production requires knowing the preferences of the talented individuals making decisions about where to locate and the constraints they face. To measure these constraints and preferences, we conducted a novel survey in 2019 of 610 recent IMO participants (see Table A1 for summary statistics). The main focus of the survey was on the decision of where to study for an undergraduate degree, as this plays an important role in shaping subsequent career paths. In addition to asking about which universities they applied to, were admitted to and attended, we also asked a series of questions where respondents were asked to make choices between hypothetical university offers in different countries—where offers were either funded or unfunded.

Figure 3 uses the survey data to show two possible global allocations of talent, distinguishing between talent born in developing countries and talent born in advanced countries. Figure 3a and 3b show the allocation that would occur if survey respondents could study at their most preferred institutions ("If you could have studied anywhere for your undergraduate degree, where would you have wanted to study?"). By contrast, Figure 3c and 3d show where survey respondents actually studied. The results suggest that the gap in where students would prefer to study and where they actually do study is quite large. Among developing participants, as many as 66% dream to study in the U.S. while only 11% dream to study in their origin country (Figure 3b). In the current allocation, 25% of participants from developing countries actually study in the U.S and 51% study in their origin country (Figure 3d).

Figure A2 depicts the gap between the dream and reality of studying in the U.S. over time. Enrollment and the dream to study in the U.S. has been rising over time among IMO participants from 2010 and 2018, despite the rising possibility of more restrictive immigration policies (e.g. restrictions on the possibility of working in the U.S. after graduation). Moreover, the gap between dreams and reality has grown over time. In the latest cohort from 2018, about half of *all* non-U.S. IMO participants dreamt of studying in the U.S., while only 15% actually enrolled in an U.S. undergraduate institution.[10]

Financing appears to be a key constraint driving the gap between the dreams and the actual destinations of study among talented youth. Forty percent of respondents report that the availability of financial assistance was a 'very important' or 'extremely important' factor in their decision to attend their undergraduate institution rather than a different one (rising to 56% for developing country participants).

To further investigate the importance of financing constraints, we turn to the hypothetical choice questions. Respondents were asked to choose between two university offers, which were structured to present an unfunded offer from a higher ranked institution (according to the Shanghai rankings) and a funded offer from a relatively lower ranked institution in the same country. We find that respondents overall chose the funded offer 54% of the time, while the share was as high as 81% for students from developing countries. In a regression of choosing the funded offer on whether a respondent is from an advanced country, including fixed effects for the pair of choices, we find that developing country respondents are 27% more likely to choose the funded offer compared to advanced country respondents (p=0.36) (see Table 4).

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[10] We also conducted a hypothetical choice analysis to identify what the short-term costs of a U.S. border closure would be (such as due to the pandemic or restrictive immigration policies). Under the U.S. border closure scenario, the share of IMO participants studying in their origin country would rise to 71% (that is 40% higher than current levels), as most of the immigrants currently going to the U.S. do not have non-U.S. admission offers.

Thus, overall, our findings strongly suggest that limited financing availability is the main factor driving the gap between dreams vs. actual destinations of study among talented youth.

IV. e. Policies to Reduce Immigration Barriers: Green Cards vs. Scholarships?

Easing financial constraints (e.g. through scholarships) can be one effective policy lever to attract talented foreign students to the U.S. Another policy that has been discussed by policymakers is increasing the number of visas offered for permanent work-based immigration (e.g. in November 2020 President-Elect Joseph Biden's immigration plan stated that "*foreign graduates of a U.S. doctoral program should be given a green card with their degree and that losing these highly-trained workers to foreign economies is a disservice to our own economic competitiveness.*") In this context, our survey data allows us to assess the potential effectiveness of improving the immigration climate through policy changes such as offering green cards—and therefore reducing the immigration certainty and improving the immigration climate more generally—to talented foreign students who study in the U.S.

Our analysis leverages a survey question where we asked respondents why they did not apply to U.S. undergraduate institutions. We find that only a small minority of respondents (around 11-15%) in either the developing or advanced country group cite the immigration climate as very important in their decisions not to apply to U.S. schools (see Figure A3). A much larger share cite tuition or living costs as a very important reason not to apply to U.S. institutions (57% among developing country participants and 37% among advanced country participants). These results suggest that relaxing financing constraints could be much more effective than improving the immigration climate.

The green card policy can be interpreted as a pull incentive (making the rewards of migrating to the U.S. more attractive) and financial assistance as a push program (reducing the

constraints for talented individuals to realize their dreams). Prior work broadly suggests that while pull incentives can be potentially important for stimulating scientific discoveries, targeted push programs could be an effective complementary tool for the advancement of the knowledge frontier (Maurer 2006, Williams 2012). In terms of attracting top global talent, our results suggest that both types of policies work as complements. However, if policymakers have limited political capital at their disposal, then prioritizing scholarships for talented students may be significantly more effective than improving the immigration climate through policies like the promise of a green card after graduation. The key intuition behind this result is that a large majority of top talent already dream of studying in the U.S., however, over half of them are unable to study in the U.S.—chiefly due to financing constraints. Making the immigration climate more attractive such as through automatic green cards works to expand the pool of dreamers, without relaxing the more binding constraint of financing for those already desiring to come to the U.S.

IV. f. Consequences of Reducing Immigration Barriers for the Advancement of Global Science

We next ask what global knowledge production would look like if policy changes lead to a lowering of immigration barriers. Combining the different components of our analysis, we derive a back-of-the-envelope estimate for the increase in knowledge production that would follow from a scenario in which all IMO participants who dream of studying in the U.S. are able to do so. The results of this exercise are illustrative, with the aim of putting initial estimates on this broad policy question. We find that under the scenario in which all IMO participants who dream of studying in the U.S. are able to do so, the total scientific output of each future cohort would increase by

42%.[11] This result is mainly driven by the productivity premium that is enjoyed by the foreign talent in the U.S.

V. Discussion

Using a range of novel data, this paper presents four key results about the impact of U.S. immigration barriers on global knowledge production. Overall, we find that immigration barriers—mainly due to financing constraints—are likely preventing the global talent pool to realize their full potential, thereby hurting the advancement of global science.

A few limitations of our study must be noted. First, regarding our results on productivity differences, one concern could be selection bias. That is, immigrants to the U.S. could be positively selected—above and beyond the IMO score that we control for. This would lead us to overestimate the effect of migration to the U.S. on productivity. We have partially mitigated the concern about selection by controlling for the IMO score during one's teenage years, which is a strong predictor of future productivity (Agarwal & Gaule 2020). But there may still be concerns about selection bias due to unobserved differences in talent or motivation. A second limitation of our study is related to our survey. There may be concerns due to selective response to the survey. However, the large sample of respondents (610) from a range of countries and participation years (Table A1) alleviate concerns about bias due to sample selection.

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[11] Among survey respondents, 67% are stayers, 15% are migrants to the U.S. and 19% are migrants to other countries. If all respondents who have their dream undergraduate institution in the U.S. could indeed study in the U.S., the share of migrants to the U.S. would jump to 41%, with the share of stayers going down to 48% and the share of migrants to other countries would go down to 11%. Our migrant productivity regressions suggest that migrants to the U.S. are 4.2 (exp(1.65)-1) times more productive than stayers and migrants to other countries are 2.2 times more productive than stayers. Total output would be 42% higher [(0.48*1+0.41*4.2+0.11*2.2) / (0.67*1+0.15*4.2+0.19*2.2)]. This calculation assumes that the productivity difference between stayers, migrant to the U.S. and migrants to other countries can be interpreted causally and does not depend on the number of stayers and migrants.

Second, some of our results rely on hypothetical questions to elicit preferences about the importance of financing constraints. One concern could be about the external validity of these methods. However, recent work (Hainmueller, Hangartner, Yamamoto 2015) suggests that conjoint pair survey designs, such as our case in which respondents evaluate two university offers side by side, may come close to the behavioral benchmark.

A third limitation of our study pertains to the back-of-the-envelope calculation. One might worry that the arrival of more migrants in the U.S. could crowd out natives or previous immigrants of faculty positions or graduate programs spots. Conversely, additional migrants could generate positive knowledge spillover. The direction and magnitude of these effects are ambiguous as documented in prior work (Moser, Voena & Waldinger 2014; Borjas & Doran 2012; Ganguli 2015). While we assume that they are small relative to the direct effects of immigrants in our estimates, further research is needed to better understand the net effects. This caveat should be noted when discussing these results of the back-of-the-envelope calculations. However, even a relatively smaller U.S. migration production premium than what we estimate—either due to selection effects or crowding out effects—would likely still translate into a sizable effect of enabling financially constrained top talent to study in the U.S. on global scientific output. This is because our estimated magnitudes of productivity differences between U.S. and other destinations are large and in the order of four to six times.

A thorough examination of why and how U.S. immigration barriers matter is timely from the perspective of global science. By preventing many of the world's brightest talent from studying and working where they have been most productive, high immigration barriers are likely to hurt both the talented individuals and the advancement of global knowledge. Even in the absence of immigration policy changes or uncertainty, a reduction in migration to the U.S. might occur due

to COVID-19. Additionally, U.S. borders may be less open in the future due to potentially rising nationalism. The scale of the threat to the advancement of science remains sizable.

Looking ahead, over the longer run, new talent hubs may emerge outside the U.S. and the global knowledge network may reconfigure itself. A key factor that may make migrants to the U.S. particularly productive is the possibility of interaction with other talented individuals who migrate there. Similarly, the U.S. may be a dream destination for many talented youth in part because other talented individuals have moved there. There is no reason a similar dynamic could not occur in countries such as the U.K., Germany, Switzerland, Canada, Italy, Switzerland, Singapore or the United Arab Emirates. For that to occur, however, a country aspiring to become a talent hub will likely need to address financing constraints as a first priority. That step alone could potentially alter global talent flows significantly—as there exists a pool of well-identified talented teenage talent in several scientific fields (e.g. mathematics, physics, chemistry, etc.).

In particular, the success of the U.S. in attracting top talent has been largely predicated on the targeted strategies of a few universities such as MIT (which attracts 25% of foreign IMO participants in our sample) of actively recruiting top foreign talent with funded admission offers. Thus, the adverse impact of continuing U.S. immigration barriers to the global advancement of science can be mitigated if other countries are able to replicate the existing 'U.S.-MIT' model of combining (i) stable open borders, (ii) full scholarships for top talent (especially for those coming from lower income countries), and (iii) a top-ranked university serving as a home for global talent.

Both political economy and budgetary challenges may, however, make it difficult for other countries to simultaneously create all three factors. Nevertheless, our analysis suggests that there may be other opportunities available to the global scientific community. For instance, the recent actions of some top universities to create a second campus in countries with relatively open borders

could offer promise to achieve the trifecta. Notably, schools such as New York University in Abu Dhabi or the Yale-National University of Singapore campus in Singapore were mentioned as dream schools in our survey. Another model is provided by The Instituto de Matemática Pura e Aplicada (IMPA), a public institution in Brazil that has been a hub for talent from all over South America. Thus, geographic re-location of learning centers could be one alternate approach to potentially overcome the adverse impact of immigration barriers on global science. In the same vein, improving centers of learning in developing countries to nurture domestic talent will also likely be helpful.

Immigration barriers—especially due to financing constraints but also more recently due to the pandemic and policy changes—ends up depriving several talented individuals from the opportunity of nurturing their talent. Furthermore, such barriers compel many talented youth to be matched with unfavorable educational environments not aligned with their preferences. Timely action by global policymakers and the scientific community is needed to ensure both equal opportunities for talented individuals and to accelerate the global advancement of science and knowledge.

Appendix: Select Questions from the Survey Instrument

This section presents select questions from the survey instrument, with an emphasis on the questions that are inputs for our main results.

Q1 What was/is the name of your undergraduate degree institution?
_____ Click to write Item 1 (1)

Q2 If you could have studied anywhere for your undergraduate degree, where would you have wanted to study?
_____ Click to write Item 1 (1)
_____ Click to write Item 2 (2)
_____ Click to write Item 3 (3)
_____ Click to write Item 4 (4)
_____ Click to write Item 5 (5)

Q3. Below are names of some of the U.S. and U.K. universities that rank highly in various national and international rankings of mathematics departments. Did you apply to one or more these universities for your undergraduate degree in each of these groups?

	Yes (1)	No (2)
MIT, Stanford, Princeton, Harvard, NYU, UCLA, Berkeley (1)	○	○
Wisconsin, Stony Brook, Rutgers, Chicago, UC San Diego, University of Texas at Austin, Columbia, Michigan (2)	○	○
Cambridge, Oxford (3)	○	○
Warwick, Imperial College, Edinburgh (4)	○	○

Q4. If you didn't apply to several of these universities, which of the following were factors in your decision not to apply?

	Very important (1)	Moderately important (2)	Not important (3)
Low probability of being admitted (1)	○	○	○
Tuition costs (2)	○	○	○
Living costs (3)	○	○	○
Preference to stay in my home country (4)	○	○	○
Preference to be close to my family (5)	○	○	○
Applications costs, including SAT and TOEFL (6)	○	○	○
Immigration climate (7)	○	○	○

Q5. Suppose you had the choice between these two admission offers. Which one would you choose

College admission offer #1
University: University of Cambridge
Location: Cambridge, United Kingdom
Financial support: No financial support

College admission offer #2
University: University of Manchester
Location: Manchester, United Kingdom
Financial support: Full financial support

	Prefer left (1)	Indifferent (2)	Prefer right (3)
Which offer do you prefer? (1)	○	○	○

Note: each respondent had four counterfactual choice questions of this type.

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Tables

Table 1. Migrant productivity regressions

	(1)	(2)	(3)	(4)
Dep. Variable->	Cites-weighted math publications		Becoming speaker at the International Congress of Mathematicians	
Migrant	1.445***		0.033***	
	(0.218)		(0.009)	
Migrant to the U.S.		1.653***		0.052***
		(0.216)		(0.013)
Migrant to the U.K.		1.020***		0.007
		(0.368)		(0.018)
Migrant to other countries		1.158***		0.010
		(0.294)		(0.010)
IMO points score FE	Yes	Yes	Yes	Yes
Country of origin FE	Yes	Yes	Yes	Yes
Year of IMO participation FE	Yes	Yes	Yes	Yes
Observations	2,195	2,195	2,272	2,272
Mean of Dep. Variable for Stayers	38.1	38.1	0.008	0.008

These regressions are run on the sample of IMO medalists participating at the IMO between 1981 and 2000. Specifications in column 1 and 2 use mathematics publications weighted by the number of forward cites received until 2017 as dependent variable and are estimated with Poisson regressions. Specifications in columns 3 and 4 use the propensity to become a speaker at the International Congress of Mathematicians as dependent variable and are estimated with OLS. Robust Standard errors in parentheses. $^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$

Table 2. Migration and occupations

Panel A	(1) Academia (math)	(2) Academia (not math)	(3) Finance	(4) IT
Migrant	0.238***	0.158***	0.060***	0.146***
	(0.022)	(0.019)	(0.012)	(0.018)
IMO points score FE	Yes	Yes	Yes	Yes
Country of origin FE	Yes	Yes	Yes	Yes
Year of IMO participation FE	Yes	Yes	Yes	Yes
Observations	2,272	2,272	2,272	2,272
Mean of Dep. Variable for Stayers	0.179	0.083	0.028	0.054

Panel B	(1) Academia (math)	(2) Academia (not math)	(3) Finance	(4) IT
Migrant to the U.S.	0.208***	0.157***	0.038***	0.202***
	(0.028)	(0.024)	(0.014)	(0.025)
Migrant to the U.K.	0.264***	0.116**	0.257***	-0.012
	(0.066)	(0.053)	(0.059)	(0.025)
Migrant to other countries	0.281***	0.171***	0.038**	0.099***
	(0.036)	(0.032)	(0.019)	(0.027)
IMO points score FE	Yes	Yes	Yes	Yes
Country of origin FE	Yes	Yes	Yes	Yes
Year of IMO participation FE	Yes	Yes	Yes	Yes
Observations	2,272	2,272	2,272	2,272
Mean of Dep. Variable for Stayers	0.179	0.083	0.028	0.054

These regressions are run on the sample of IMO medalists participating at the IMO between 1981 and 2000. Occupations were manually collected from online profiles, LinkedIn and similar sources; individuals who could not be found online are coded as not being in any of the four occupations. Robust Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 3. Migrant productivity regressions conditional on being in math academia

Dep. Variable->	(1) Cites-weighted math publications	(2) Cites-weighted math publications	(3) Becoming speaker at the International Congress of Mathematicians	(4) Becoming speaker at the International Congress of Mathematicians
Migrant	1.053*** (0.231)		0.074*** (0.026)	
Migrant to the U.S.		1.329*** (0.250)		0.129*** (0.036)
Migrant to the U.K.		-0.021 (0.359)		0.027 (0.038)
Migrant to other countries		0.569* (0.310)		0.002 (0.022)
IMO points score FE	Yes	Yes	Yes	Yes
Country of origin FE	Yes	Yes	Yes	Yes
Year of IMO participation FE	Yes	Yes	Yes	Yes
Observations	527	527	548	548
Mean of Dep. Variable for Stayers	161.3	161.3	0.043	0.043

These regressions are run on the sample of IMO medalists participating at the IMO between 1981 and 2000 who were employed in math academia as of 2017. Specifications in column 1 and 2 use mathematics publications weighted by the number of forward cites received until 2017 as dependent variable and are estimated with Poisson regressions. Specifications in columns 3 and 4 use the propensity to become a speaker at the International Congress of Mathematicians as dependent variable and are estimated with OLS. Robust Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table 4. Counterfactual choice regressions

	(1)	(2)
	Dependent variable= choose funded offer (0/1)	
From a developing country (0/1)	0.270***	0.196***
	(0.036)	(0.056)
Medalist (0/1)		-0.113**
		(0.048)
From a developing country x medalist		0.136*
		(0.072)
Choice Fixed Effects	Yes	Yes
Observations	1539	1539
Mean of dependent variable	0.54	0.54

Survey respondents were asked to choose between two offers for undergraduate admissions. The offers were structured to involve an unfunded offer from a higher ranked institution (according to the Shanghai rankings) and a funded offer from a somewhat lower ranked institution. The regression analyze the propensity to accept the funded offer in these counterfactual choices. Standard errors in parentheses. $^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$.
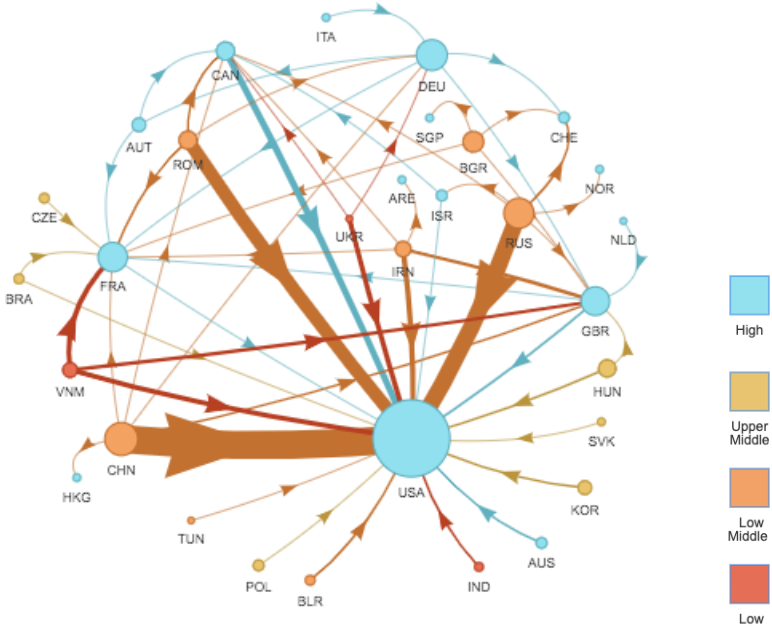
Figures

Figure 1A. Global Knowledge Network for Nobel Prize winners in Chemistry, Physics and Physiology or Medicine from 2000 to 2019
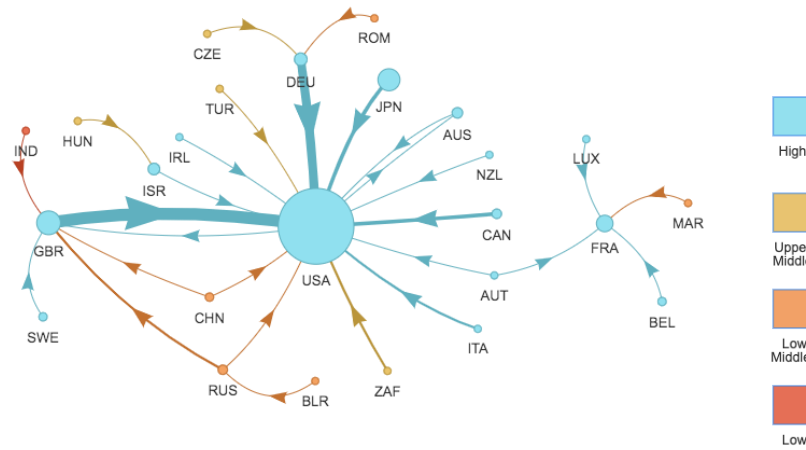
Notes: This figure is a weighted, directed network graph where the nodes are countries and the edges with arrows represent flows from prize winners' countries of birth to countries at the time of award. Thicker edges indicate larger flows. The nodes are weighted by the number of prize winners in the country at the time of award. We classify countries into high income, upper middle, lower middle and low income based on the 2000 World Bank classification.

Figure 1B. Global Knowledge Network for IMO gold medalists 1981-2000.

Notes: This figure is a weighted, directed network graph where the nodes are countries and the edges with arrows represent flows from gold medalists' origin countries (at the time of the IMO competition) to current country. Thicker edges indicate larger flows. The nodes are weighted by the number of gold medalists currently in the country. We classify countries into high income, upper middle, lower middle and low income based on the 2000 World Bank classification.

Figure 2. Share of migrants to the U.S. in frontier knowledge production

Nobel prizes winners in Science

- 21% — Migrants to the U.S.
- 11% — Migrants to other countries
- 35% — U.S. stayers
- 33% — Other stayers

Fields medals

- 33% — Migrants to the U.S.
- 30% — Migrants to other countries
- 7% — U.S. stayers
- 30% — Other stayers

Legend:
- Migrants to the U.S.
- Migrants to other countries
- U.S. stayers
- Other stayers

Figure 3. Studying abroad: dream and reality

a: Advanced countries: actual

c: Advanced countries: dream

b: Developing countries: actual

d: Developing countries: dream

USA   UK   Other countries   Origin country
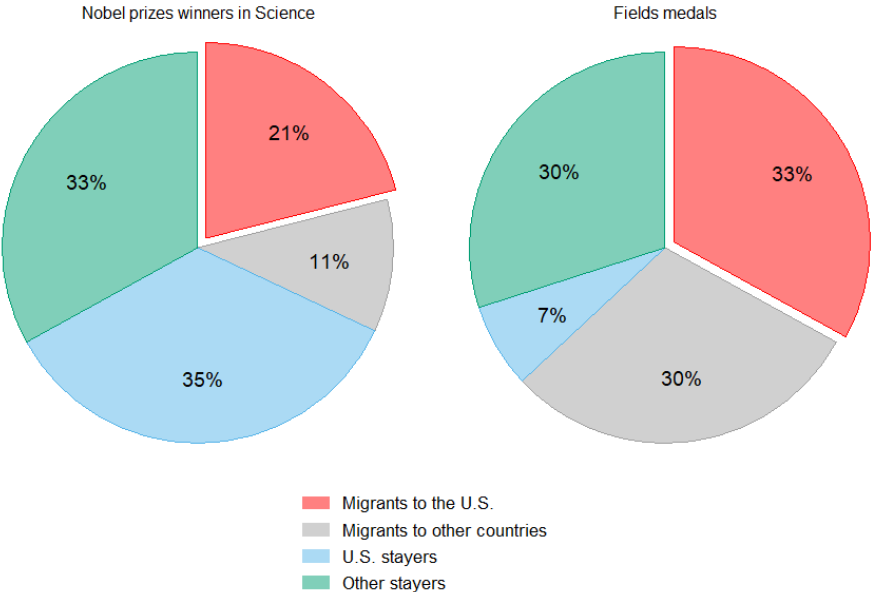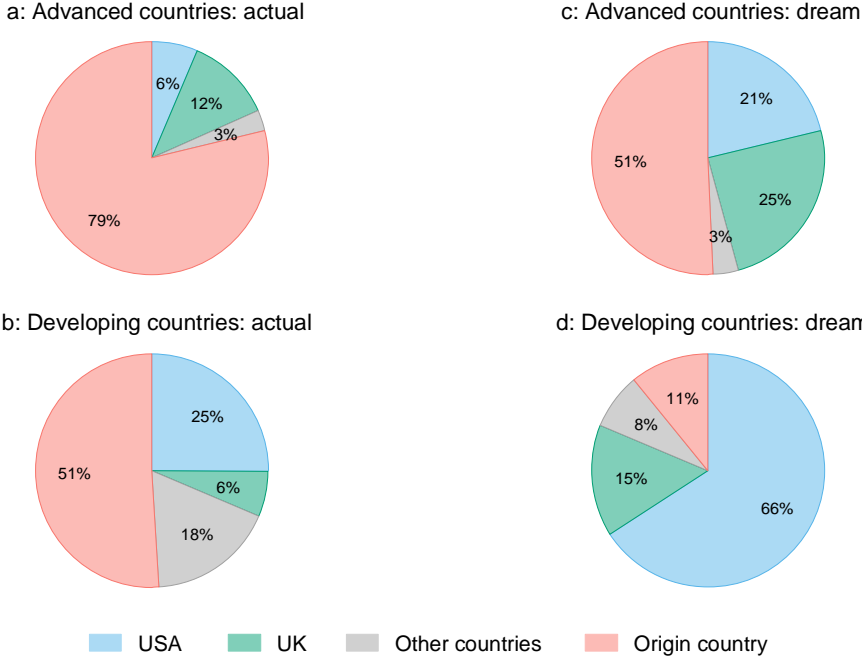
Notes: This figure is based on a survey of recent participants of the International Medal Olympiads. We asked respondents where they enrolled for their undergraduate studies (panel a and b) and where they would have wanted to study if they could have studied anywhere in the world (panel c and d).

Appendix Tables

Appendix Table A1. Summary Statistics of Survey Respondents vs. All IMO participants

Sample Means	IMO participants (2009-2018)	Survey respondents	Difference
Received a medal	0.498	0.549	0.052**
	(0.500)	(0.498)	(0.021)
Region of origin (World Bank region):			
Europe and Central Asia	0.505	0.579	0.073***
	(0.500)	(0.494)	(0.021)
North America	0.028	0.020	-0.008
	(0.165)	(0.139)	(0.007)
East Asia and Pacific	0.172	0.148	-0.025
	(0.378)	(0.355)	(0.016)
Latin America and the Caribbean	0.130	0.179	0.048***
	(0.337)	(0.383)	(0.015)
South Asia	0.043	0.010	-0.033***
	(0.202)	(0.099)	(0.008)
Middle East and North Africa	0.073	0.030	-0.043***
	(0.260)	(0.169)	(0.011)
Sub-Saharan Africa	0.049	0.036	-0.013
	(0.216)	(0.187)	(0.009)
Observations	5,666	610	6,276

Appendix Figures

Figure A1. Talent ratios: talent living in country/talent produced by country based upon IMO medalists

Talent ratios: talent living in country/talent produced by country

USA
Switzerland
UK
France
Germany
Spain
Canada
Brazil
Hong Kong
Sweden
Japan
Netherlands
Austria
Russia
Taiwan
Singapore
Israel
South Korea
Australia
Poland
Belgium
Vietnam
Italy
Bulgaria
Belarus
Hungary
Ukraine
China
Turkey
Iran
India
Romania
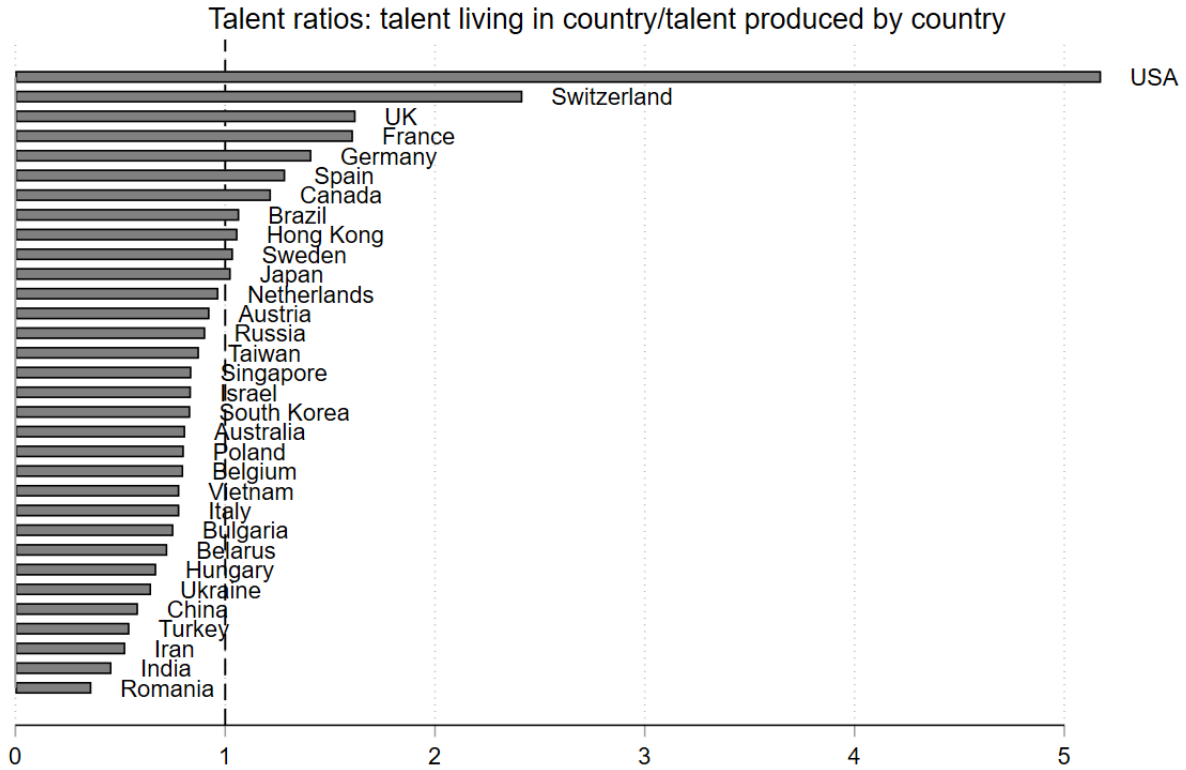
0   1   2   3   4   5

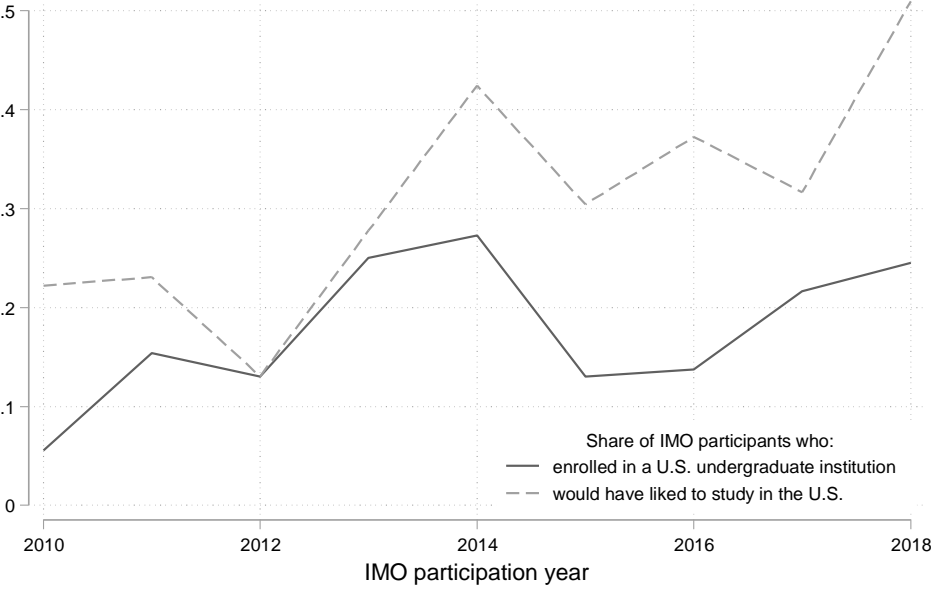**Fig. A2: Studying Abroad: Dream vs. Reality over time**

Fig. A3: Role of Financial Costs vs. Immigration Climate: Share of Respondents Citing Financial Costs or Immigration Climate as 'Very Important' Reason for Not Applying to US Institutions

Developing Country Respondents

Financing Costs
Very Important
(48%)

Both
(9%)

Immigration Climate (6%)

Neither Very
Important
(38%)

Developed Country Respondents

Financing Costs
Very Important
(31%)

Both
(6%)

Immigration Climate (5%)

Neither Very
Important
(57%)