Journal of International Money and Finance 131 (2023) 102802

Contents lists available at ScienceDirect

Journal of International Money and Finance

journal homepage: www.elsevier.com/locate/jimf

Technology and the geography of the foreign exchange market

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ARTICLE INFO

Article history:
Available online 20 January 2023

JEL code:
F30

ABSTRACT

We analyze the impact of technology on the production and trade in services, focusing on the location of foreign exchange transactions and the effect of submarine fiber-optic cable connections. Cable connections between local markets and major financial centers reduce the costs of trading currencies locally and increase the share of currency transactions taking place in the issuing country. But they also attenuate the effect of existing spatial frictions that prevent transactions from moving offshore to take advantage of agglomeration economies and thick-market advantages of major financial centers. In practice, this second effect dominates. Our estimates suggest that the advent of cable connections boosted the share in global turnover of London, the world's largest trading venue, by as much as one-third.

1. Introduction

High-speed, low-cost communication is a distinguishing feature of the 21st century. What it implies for the geography of trade and production is unclear, however. It has been argued that ubiquitous communication allows service-sector activities that benefit from agglomeration, spillovers and thick markets to concentrate in a handful of major centers and then for their products to be distributed to the rest of the world.[1] But cheap, high-speed communications also allow activities not benefiting from agglomeration to be spread more widely across the global economy, without significant sacrifice of managerial control, in response to rising costs in particular locations.[2] One can point to the City of London for finance and Silicon Valley for technology and innovation as examples of the former, and assembly operations and global value chains as instances of the latter.

In this paper we investigate these questions in the context of the global foreign exchange market. This is an appealing case for several reasons. The foreign exchange market is one of the largest financial markets in the world as measured by transactions, with an average daily turnover in the order of $6 trillion. It is a market in financial services, as opposed to merchandise, which makes it relevant for thinking about the geography of activity in a post-industrial age. And it has undergone a dramatic transformation since the late 1980s, reflecting the availability of cheap and efficient information and communications and the growth of electronic trading.

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1 For theoretical treatments see Krugman (2011) and Duranton and Puga (2004).
2 As argued for example by Cairncross (1997).

https://doi.org/10.1016/j.jimonfin.2023.102802
0261-5606/

Investments in technology can affect the geographical distribution of economic activity, but changes in the geographical distribution of economic activity also provide an incentive for investments in technology. Examples of sharp, discontinuous, exogenous changes in information and communication technology would help to pin down the causal effect, but technological progress tends to be continuous rather than discrete, endogenous rather than exogenous. Instances where it is possible to identify the diffusion of technology shocks over economic and geographical space are few and far between.

But in the case of the foreign exchange market, we have just such a source of exogenous change and spatial variability. This is the laying of submarine cables starting in the late 1980s. With different cables coming into use at different points in time, both the cross section and time series help us to identify the effects of technology on the location of foreign exchange transactions.

Direct and indirect connections via a submarine fiber-optic cable increase bandwidth (i.e. data throughput per unit of time). Greater bandwidth reduces the costs of aggregating and matching buy and sell orders and cuts the costs of processing information and data more generally. This is attractive to traders using other internet-based applications such as e.g. Bloomberg, Haver Analytics or Datastream.[3]

If these gains are large, they can affect the geography of trading and the relative importance of other determinants of the location of trading. The effect is similar to the effect of reductions in transportation costs on purchases and sales of merchandise by counterparties in different locations, as in Krugman (1980, 1985). As in Krugman's model, lower costs encourage transactions to migrate toward the largest, most active markets (here the largest, most liquid financial centers). The effect can be cumulative and self-reinforcing: lower transportation costs (here, increased bandwidth due to cable connections) cause activity to move to the largest (here, most liquid) markets, whose size (liquidity) increases further as a result, attracting yet more transactions.[4]

But the effect could also go in the opposite direction, to the extent that reduced costs give local counterparties better information about market conditions. Here, cable connections may enable the local sales desk to access to a more timely and broader set of quotes as well as other financial information and enable them to communicate more easily with a matching servers offshore. To continue with the analogy with Krugman's model, a growing share of transactions occur at home when lower communications costs reduce local costs of transacting.

We find evidence of both effects. On balance, however, we find that cable connections increased the share of foreign exchange transactions in the three major forex trading centers. This technology increased the share of offshore trading by 21 percentage points overall. It had economically important implications for the distribution of foreign exchange transactions across financial centers, boosting the share of global turnover of London, the world's largest trading venue, by as much as a third.[5]

We treat the presence of a cable link between two countries as exogenous with respect to foreign exchange trading for reasons of geography, history, safety, market needs, and cost. However, we also apply an instrumental variables strategy using the 3-dimension length of submarine fiber-optic cable routes.[6] We use these features of the natural environment to extract the exogenous component of whether and when countries were connected to the internet backbone.

Our results relate to the findings of earlier studies of the effects of broadband internet on the geography of international trade. Akerman et al. (2018), in a study of Norway, find that broadband internet increased the elasticity of trade in goods with respect to distance and economic size. Malgouyres et al., 2021 find that the rollout of broadband in France corresponded to an increase in the value of goods imported by small and medium-sized firms, a class of producers that, they argue, are subject to significant information frictions.[7]

Section 2 takes up the question of whether the submarine fiber-optic cable network should be regarded as exogenous with respect to the foreign exchange market. Section 3 describes the data, Section 4 stylized facts, Section 5 describes our identification strategy. Section 6 discusses our empirical framework and hypotheses, while Section 7 reports the basic results. Section 8 presents IV estimates and Section 9 various robustness checks. Section 10 gauges the distributional effects of cable connections across the world's financial centers, after which Section 11 concludes.

2. Exogeneity

We treat the existence of a cable link between two countries as exogenous with respect to foreign exchange trading for reasons of geography, history, safety, market needs, and cost.

[3] That in 2012 the bandwidth consumption of Singapore, a major financial hub, was three times that of South Korea, a country known as a hub of gaming and other non-financial internet-based activities whose population is ten times larger, is suggestive of its importance for financial applications.

[4] A difference from Krugman (1980)'s model is that he considered two types of goods of different varieties whereas we focus here on one type of services, i.e. foreign exchange transactions in different units. In a related model, Gehrig (1998) observes that a decline in transportation costs strengthens the impact of thick market externalities and the position of incumbent markets.

[5] The dampening effect of cable connections on the standard gravity trade determinants is robust to an instrumental variable strategy using the 3-dimension length of the cables in question, buttressing our causal interpretation.

[6] This builds on work by Juhász and Steinwender (2018), who previously employed sea-floor topological irregularities arising from nature, such as domes, canyons and faults, as a source of variations that is exogenous to financial and economic activities.

[7] Using the international rollout of telegraph cables in the 19th century, Wache (2020) show that reductions in information frictions had a significant and positive impact on the bilateral international flow of financial capital from the UK.

The presence or absence of a submarine fiber-optic connection is influenced by seabed geography. Submarine cables can only connect terrestrial points with direct access to the ocean. Over half of fiber-optical cable network nodes are on islands (Starosielski 2015). Singapore, which is a peninsula, has more cable connections (21) than mainland China (12). Guam has as many cable connections (10) as Germany. Landing points are chosen in areas with gently sloping, sandy or silty sea-floors and without strong current to minimize risks of damage. That Iceland is surrounded by mid-ocean ridges explains, for instance, why three of its four cable connections were only established in the 2000 s, late in the sample period.

History also shaped the fiber-optic network. The contours of the current network broadly follow those of the telegraph network laid in the nineteen century and of the coaxial network laid in the 1950s through 1970s. Fiber-optic cables connecting New Zealand, for example, are located in almost exactly the same places as telegraph cables laid in the late 19th and early 20th centuries. This reflects considerations of geography and current cited above. It reflects learning from this earlier experience: a history of system failures due to currents, interference from fishing vessels and natural disasters encourages modern cable companies to ply historical routes.[8]

Geopolitics is another factor in persistence. Once a route is seen by the cable industry as secure because it has been shown to be sheltered from man-made interference such as wars, sabotage, and terrorist attacks, there is a tendency to maintain it.[9]

A reading of industry publications indicates that fiber-optic cables were not laid for reasons related to the foreign exchange market. Their underwriters foresaw them as efficient and profitable vehicles for carrying long-distance telegraphic communication, telephone calls and fax traffic, only a small portion of which was related to trading foreign exchange.[10] Press reports from the late 1980s and early 1990s highlight prospective increases in efficiency and capacity for telephony, fax and television transmission. An article published in the *New York Times* on inauguration of the first transatlantic fiber-optic cable stressed that it would "vastly increase the number of calls that can be placed to Europe at one time" and "will provide international telephone calls and data transmissions free of delay and distortion" (Sims, 1988).

Additional impetus in the 1990s came from development of the internet, access to which required cables (prior to the subsequent age of cheap and efficient satellite communications). To be sure, it was anticipated that the internet would be useful for a range of business applications, including some of interest to financial markets.[11] But financial applications were not the main motivation for building out the internet backbone in the 1990s and early 2000s.[12]

Finally, submarine fiber-optic cables are typically owned by large telecommunication consortiums, not by financial institutions. The SEA ME WE 4 cable connecting South East Asia, the Middle East and Western Europe is owned by 17 telecom companies from 17 nations. These companies act as dealers selling bandwidth to mobile phone companies and internet providers. Among the wide range of customers of these internet providers may be financial market participants, but these are typically dwarfed in importance by other customers – that is to say, investment in cables was undertaken principally with these other customers in mind.

Endogeneity might still enter through omitted variables that influence both the share of trading occurring offshore and cable access. Financial deepening may create incentives to connect a country to the network of undersea cables, for example, and encourage financial innovations and investments in market infrastructure that buttress onshore trading. Insofar as this dampens the estimated effect of cable connections on offshore trading, our estimates would be biased downward (and should be regarded as a lower bound on the effect of cable connections).

It might also be argued that the presence of a cable is endogenous because its existence is related to general telecommunication needs that are a function of population size, which in turn affects the level of financial market activity. However, our dependent variable, as we explain below, is the share of the domestic currency traded offshore, not domestic foreign exchange turnover (or the level of financial activity). This transformed measure varies widely across countries with similar levels of financial depth. For instance, the shares of US dollar and sterling transactions taking place offshore stood at about 80 per cent and 40 per cent respectively, in 2013; yet both currencies are issued by nations with the largest and most liquid foreign exchange markets globally. Be this as it may, instrumental variables estimates confirm our central findings.

Another concern might that timing of access to the internet backbone is not exogenous because the laying of submarine fibre-optic cables clusters between 1989 and 2002. Empirical estimates could be driven by confounding factors such as foreign exchange traders' expectations of using the cable network profitably, the emergence of high frequency trading, and the introduction of the euro. Table A18 provides evidence that foreign exchange market potential is unlikely to have influenced

[8] Examples of natural disasters impacting the internet backbone are numerous, a recent famous one being Japan's tsunami in 2011, which also broke several fiber-optic cables.

[9] The early telegraph network of the nineteen century was mapped over colonial geographies for military reasons. For instance, several telegraph cables laid by the British Empire landed only on imperial territory for fear of interference by foreign powers. Telegraph cables between China and the UK were famously sabotaged during the Boxer rebellion of 1899–1901. That Guam hosts a U.S. military base partly explains why it has played a key role in the cable network.

[10] The majority of companies that laid telephone cables through the 1980s were government-owned or affiliated monopolies. Most were telecommunication companies (see below and Table A2 in the online appendix for information on the owners of the cables connected with London, New York and Tokyo in 2002).

[11] For instance, an article in *The Economist* in 1994 foresaw that online services and information providers "includ[ing] stockbroking (through such firms as Bloomberg), financial information (Dow Jones), news services (Reuters) and databases (NEXIS/LEXIS)" would benefit from the development of an "information highway" capable of transmitting voice, text, video and data simultaneously.

[12] Nor have they been the motivation for more recent investments in submarine fiber-optics by Silicon Valley companies, like Google, which have invested in submarine fiber-optic cables (like those connecting Florida with Brazil and Southeast Asia with Japan). In 2010 Spread Networks unveiled an 827 miles terrestrial cable running through mountains and under rivers from Chicago (home to the Chicago Mercantile Exchange where derivatives are traded) to New Jersey (home of the Nasdaq data center). Hibernia Express, which was tested in September 2015, is the first submarine cable laid for the express purpose of electronic trading, which falls outside the sample period we consider.

the timing of cable connections. It reports estimates of an OLS cross-section regression where the dependent variable is the year when a country was connected to the network of submarine fiber-optic cables. The independent variables include foreign exchange market potential (the share of a country's foreign exchange turnover in global foreign exchange turnover in the year of connection), seabed ruggedness (which captures the existence of domes, canyons, faults, and other topological irregularities), and the 3-dimension length of the submarine fiber-optic cables (these last two variables capturing our alternative hypothesis). The estimated coefficient on market potential is statistically insignificant. The variable explains<1 % of the variance in timing of cable connections across countries (see Table A18, column 1). In contrast, the estimated coefficients on ruggedness of the seabed and 3-dimension length of the submarine fiber-optic cables are statistically significant (see Table A18, columns 2 to 4). Both variables explain a much larger share (25–30 %) of the variance in the timing of cable connections across countries, consistent with the view that foreign exchange traders' expectations of using the cable network profitably was not one of its major determinants, unlike seabed topology.

We can also reject the suggestion that high frequency foreign exchange trading provided the impetus for establishing cable connections because the timing is wrong. Figure A8 below shows the share of algorithmic trading, of which high frequency trading is one category, on EBS – one of the two leading platforms for electronic broking and trading in the sample (equivalent data for the other platform is unavailable.). The share of algorithmic trading was close to zero in 2004 – two years after the last country in the sample had been already connected to the internet submarine fiber-optic cable network.

Finally, creation of the euro is also unlikely to confound our main results below. Figure A9 shows that creation of the euro in 1999 had no effect on the share of forex transactions occurring in London, New York and Tokyo. It did lead to a mechanical reduction in turnover by eliminating intra-legacy trading (i.e. trading between the Deutsche Mark, French Franc, Italian Lira, etc.); see Galati (2001). But it did not affect the combined market share of the major forex trading centers, which remained unchanged at 54 %.

3. Data

We take data on the network of submarine fiber-optic cables from TeleGeography's interactive Submarine Cable Map.[13] These data were collected by Global Bandwidth Research, a consultancy specializing in data and analysis of long-distance networks and the submarine cable market. They provide information on 368 submarine cables starting in 1989. Information covers the cable's profile, name, year when it was ready for service, length, owners, and geographical coordinates of its landing points.

For data on the location of foreign exchange trading, we obtained confidential estimates of onshore, offshore and global foreign exchange turnover by currency from the Bank for International Settlements (BIS). We have data for 55 currencies (including 12 euro legacy currencies) in seven years (1995, 1998, 2001, 2004, 2007, 2010 and 2013). The data were collected in the context of the BIS's triennial central bank surveys of foreign exchange and derivatives market activity.[14] The number of currencies and trading locations covered by the BIS surveys has increased over time. Our baseline results utilize the full data set, but we also analyze a balanced panel.

BIS statisticians define foreign exchange turnover as the daily average of the notional amount (in US dollar equivalents) of all transactions in April of the year of the triennial survey.[15] They produce data in "net-net" terms. In other words, they adjust for local double-counting – i.e. for transactions between reporting dealers located in the same country – as well as for cross-border double-counting.[16]

[13] TeleGeography has made the source code behind the interactive Submarine Cable Map available for download at https://github.com/telegeography/www.submarinecablemap.com.

[14] These surveys offer the most comprehensive and internationally consistent information on the size and structure of the foreign exchange market although, as King and Mallo (2010, p. 71) observe, "the underlying data remain largely unexplored." An exception is e.g. He et al. (2015), who do not however focus on the impact of technology on the location of FX transactions, as here. The exact location of offshore transactions is not known, but an overwhelming share can be shown to take place in major financial centers such as London, New York or Tokyo (see below). Whether or not triannual data are too coarse or infrequent to allow us to identify the impact of the establishment of a cable connection on the location of activity is an empirical question. Our empirical results suggest that they have significant information content. Note that we are not studying the impact of a cable connection on, inter alia, daily movements in asset prices, for which higher frequency data would be desirable. In practice, moving trading activity offshore requires establishing a business relationship with a foreign partner. It requires reorganizing one's business practice. It takes time. For instance, relocation of UK-based banking activities by international banks is still ongoing several years after the Brexit referendum. All this suggests that triannual data are informative.

[15] A broad array of foreign exchange instruments are covered, including spot transactions, outright forwards, foreign exchange swaps, currency swaps, currency options and other foreign exchange products, including nondeliverable forwards. Dealers report their transactions in these instruments with other reporting dealers, other financial institutions and non-financial customers. Each transaction is recorded once, and offsetting contracts are not netted. There is no distinction between sales and purchases. Direct cross-currency transactions (e.g. pound sterling for Swiss francs) are counted as single transactions. Transactions that use a vehicle currency (e.g. the US dollar) are counted as two separate transactions. See King and Mallo (2010) for further details. The data include transactions in dark pools such as MidFX and BGC.

[16] For instance, local inter-dealer transactions in Germany are halved to obtain the correct turnover for Germany. As another example, transactions between a reporting dealer located in the United Kingdom and a reporting dealer located in France are halved to obtain the correct estimate of global turnover.

Foreign exchange turnover is allocated across countries according to where the transaction is arranged. Since 2004, BIS statisticians have specified that they mean the location of the initiating sales desk.[17] For example, when an employee of a savings bank in Berlin asks his or her foreign exchange dealer at Deutsche Bank Frankfurt to buy Y50 million against euros, this transaction will be recorded as having taken place in Germany, because the sales desk is in Germany.[18] BIS statisticians use the trading desk to determine the location of a deal when no sales desk is involved.[19] Discussions with foreign exchange dealers suggest that banks net and aggregate their positions in the same location (in the back-office) where they trade (in the front-office). In other words, there are no major differences between sales and trading desks in most cases.[20]

4. Stylized facts

Since the mid-1990s, transactions in foreign exchange have increasingly taken place at locations other than the country issuing one of the currencies involved in the trade.[21] The offshore global weighted average rose by five percentage points between 1995 and 2013, to about 78 %.[22] Insofar as this estimate is higher than the lower bound of 50 % (one of the two currencies involved in a foreign exchange trade undertaken in a particular national market is the currency of a foreign country, meaning that it is necessarily traded offshore), this confirms that a substantial fraction of transactions occur in third markets.

From 1995 to 2013 the global unweighted average of the individual currency shares of foreign exchange trading occurring offshore essentially tripled, from 20 to 60 per cent (the unweighted arithmetic average is not subject to the 50 % lower bound). This suggests that trading in third markets affected not just major currencies like the US dollar but also other units. Offshore trading increased markedly between 1997 and 2004 (when all countries in our sample were connected to the internet backbone), and continued rising thereafter. This makes it important to include time fixed-effects in our regressions to control for global developments that might drive the share of foreign exchange trading occurring offshore, such as the rise of high-frequency trading, co-location services or regulatory changes.

Not only does a substantial fraction of offshore transactions occur in markets such as London, New York or Tokyo, but that share is increasing.[23] There is, however, considerable heterogeneity among currencies in the extent of trading offshore. Fig. 1 highlights the relatively high shares of the US dollar and also the euro and Japanese yen, compared to the relatively low shares of several emerging market currencies, like the Korean won and Indian rupee, while still other emerging market units have high shares (for example the Polish zloty). In total, only 9 of the 55 units had an offshore share of<50 %. In other words, most currencies actively trade offshore.

5. Identification

We model currency trading as analogous to production of services under monopolistic competition. This is appropriate, since a limited number of electronic platforms and FX dealers dominate the market. In this setting, increasing returns arise from the self-reinforcing effect of additional market liquidity. Hence a fall in transportation costs (in our context, an increase in bandwidth resulting from establishment of a cable connection) causes additional activity to gravitate toward to the largest market, as in the model of Krugman (1980).[24]

Our identification strategy builds on the special role of the UK, the US and Japan in electronic foreign exchange trading. It is in these countries that matching servers of EBS and/or Thomson Reuters – the leading platforms for electronic broking and

[17] The nationality of the reporting dealer is not relevant in this context. For example, when UBS Frankfurt reports trades to the Bundesbank, these transactions are allocated to Germany.

[18] Actual trading could take place elsewhere, for example by traders at Deutsche Bank London. In reality the dealer will not execute every single trade individually because transaction costs would be excessive and he/she would take credit risk for each transaction. Dealers will instead add additional trading orders to their dealing books, net FX positions internally (via Autobahn, BARX or Velocity, for example) and trade the residual either on exchange platforms (EBS, Reuters, etc.) or via OTC transactions. From a BIS perspective, what matters is the location where the FX book is aggregated and netted (i.e. at the back-office).

[19] Given the growing use of electronic execution methods, moreover, in the BIS Triennial Survey conducted in April 2016 the sales contact of the electronic platform who services the client, or the trading desk or the electronic matching engine, was used to determine the location of a deal when no sales desk is involved (see BIS 2015).

[20] This is consistent with the observation that there were no major breaks in the data when the BIS changed its definition of trading location in 2004 from the trading desk to the sales desk. The distinction might be more important in the case of smaller financial centers where the sales desk remains local but the trading desk might be in a larger center, such as London, New York or Tokyo. But readers should note that when a bank decides to relocate its trading desk to a major financial center, it may move its sales team there, too.

[21] See Figure A1 in the online appendix.

[22] The weighted average is the sum of foreign exchange trading occurring offshore in all currencies scaled by the sum of total (onshore and offshore) foreign exchange trading in all currencies. The unweighted average is the arithmetic average of the individual currency shares traded offshore.

[23] This is evident from Figure A2, which shows the evolution between 1995 and 2013 of scaled and unscaled Herfindahl indices of concentration of global foreign exchange transactions occurring offshore in these three financial centers (left-hand-side panel), as well as the combined share of global transactions they account for (right-hand side panel). Both charts show a clear upward trend, testifying to the importance of London, New York and Tokyo in the global market for offshore foreign exchange transactions.

[24] Gehrig (1998) similarly shows how a decline in transportation costs can strengthens the impact of thick market externalities and thereby the position of the dominant incumbent markets.

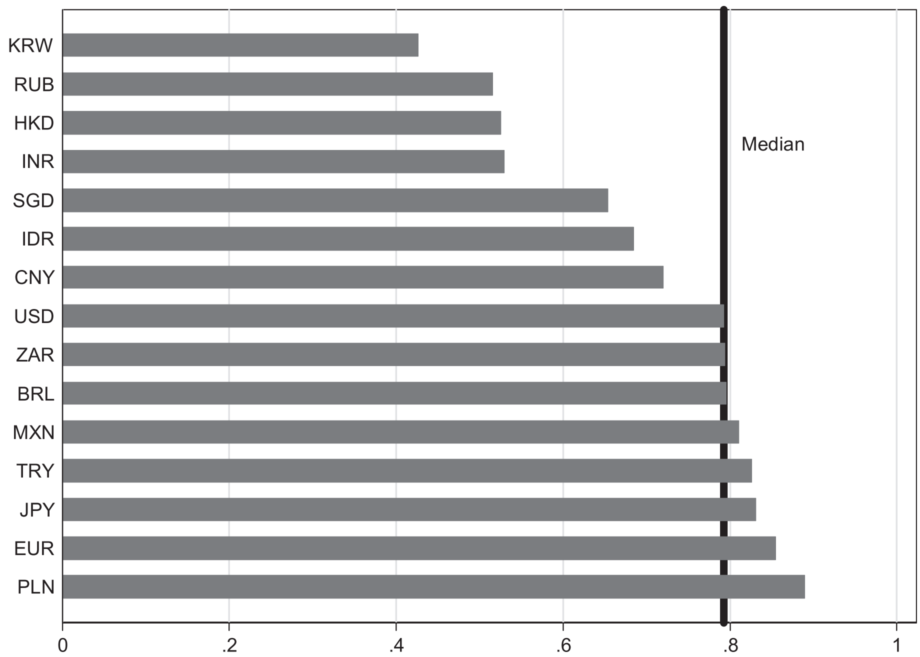

Fig. 1. Offshore Foreign Exchange Trading in 2013 – *Breakdown for Selected Currencies Notes*. This figure shows the shares of foreign exchange trading occurring offshore for the same units as in McCauley and Scatigna (2011) and Ehlers and Packer (2013). The thick black line is the (unweighted) median of all individual currency shares (including those not reported in the figure).

trading – are located. EBS servers have been located in the UK, US and Japan since 1990. Thomson Reuters has servers in both the United Kingdom and the United States.[25]

Our analysis considers when different countries were connected to the network of submarine fiber-optic cables, either directly or indirectly. "Directly" means that there is a point-to-point submarine fiber-optic cable connecting country × to the UK, US or Japan.[26] "Indirectly" means that country × is connected to country *y* and country *y* is in turn connected to the UK, US or Japan. We take into account indirect connections up to the ninth order.

Fig. 2 shows the year of first direct or indirect connection to the UK, US or Japan. France and the Netherlands were connected to the UK in 1989. South Africa, to take a contrasting example, was connected in 2002. Landlocked countries, like Switzerland or Hungary, are not connected by submarine cables for obvious reasons. We hence use for identification both the cross-section and time series dimensions, i.e. heterogeneity between landlocked countries and nations bordering the sea and heterogeneity between the period pre-2002 and the period post-2002 (in robustness checks we show that our results are robust to alternative sample periods).[27]

6. Empirical framework and hypotheses

We estimate the determinants of the share of foreign exchange trading occurring offshore as a function of cable connections and control variables. Descriptive statistics of the data used to estimate our model equations are provided in Table A16 in the online appendix. We account for the possibility of unobservable random and time effects by estimating the following specification:

$$y_{i,t} = \beta \mathbf{Z_{i,t}} + \varphi \left[\mathbf{Z_{i,t}} \times Cables_{i,t}\right] + \gamma Cables_{i,t} + \rho \mathbf{X_{i,t}} + \alpha_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

[25] EBS is predominantly used for transactions involving the US dollar, euro, yen and Swiss franc, while Thomson Reuters is predominantly used for transactions involving the pound sterling, the Australian, Canadian and New Zealand dollars, and emerging market units.

[26] In robustness checks we consider only connections to the UK, the US and Japan individually; see below.

[27] Landlocked countries can be connected only indirectly via terrestrial cables. This entails higher costs, since digging trenches, tunneling through natural obstacles and obtaining transit rights from property owners are costly and difficult (as recounted by Lewis 2014) – more costly and difficult than laying cables on the seabed. Figures A4 and A5 illustrate the growing density of the submarine cable network. They show the network of countries directly or indirectly connected to the UK in 1998 and 2013, respectively. Countries in time zones corresponding to Asian trading hours are shown as light grey nodes, against grey nodes for those located in time zones corresponding to European trading hours and dark grey nodes for US trading hours. Solid lines indicate countries with liquid units – those that are in the top third by FX turnover – while dashed lines are units in the middle third, and dotted lines are illiquid units in the bottom third. The contrast between the two figures is striking. That the network of connections to the UK has grown markedly over time, and improved access to the matching servers of EBS and Thomson Reuters for electronic trading is readily apparent.

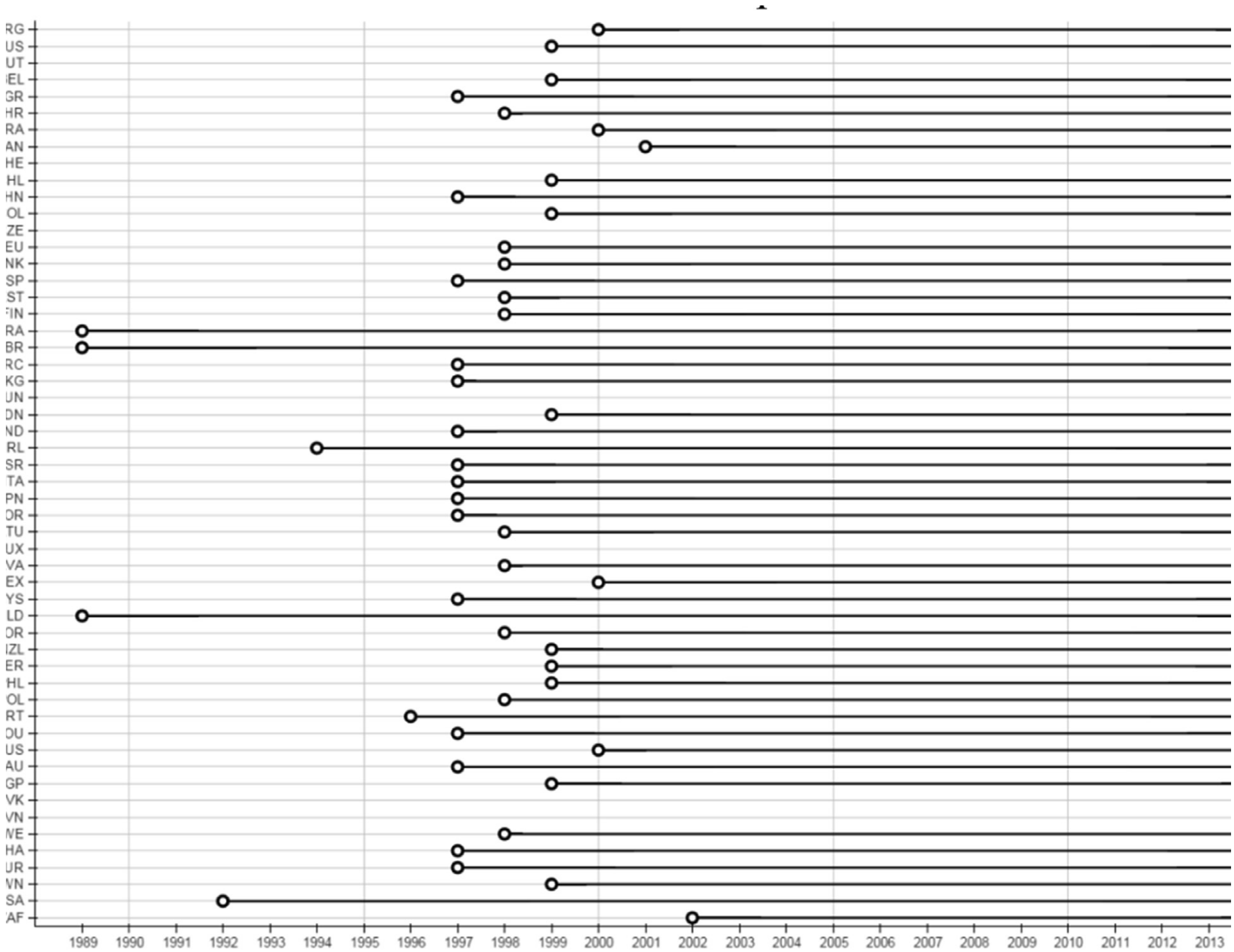

Fig. 2. Year of First Connection to the UK, US or Japan via a Submarine Fiber-Optic Cable *Notes*. This figure shows the year when the countries issuing the 55 currencies of our sample were first connected (point-to-point or via third countries) via a submarine fiber-optic cable to the U.K., the U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic foreign exchange trading are located).

where i and t denote currency and time; y is the share of trading occurring offshore for currency i in year t. $\mathbf{Z}$ = [*Time Zone Distance*$_i$, *Domestic Market Liquidity*$_{i,t}$, *Capital Controls*$_{i,t}$] is a vector of financial and geographical frictions whose effect on the location of trading may be affected by the presence of a cable connection. *Cables* is a zero/one dummy variable for the existence of a cable connection between the country issuing currency i and London, New York or Tokyo in a given year t. $\mathbf{X}$ is a vector of controls. The vectors $\boldsymbol{\beta}$, $\boldsymbol{\varphi}$, γ and $\boldsymbol{\rho}$ are the parameters to estimate. The α_i are random effects and λ_t are time fixed effects.

We estimate Eq. (1) using a panel tobit estimator and a panel generalized linear model with a logit link (both with random effects). Tobit is appropriate insofar as our dependent variable is a share whose observed range is censored below zero and above 100 percent. We also report results using linear panel and pooled OLS estimators, with standard errors robust to heteroskedasticity and clustered by trading zone,[28] The time fixed effects soak up variation in the data due to unobserved global factors such as the rise of financial institutions' proprietary trading at the expense of corporates, the emergence of algorithmic trading and co-location services in the mid-2000s, or regulatory changes (more on this below).

Focusing on market shares rather than absolute transaction volumes is appropriate because global foreign exchange turnover and cable connections both trend strongly upward over the period. (Global foreign exchange turnover quadrupled

[28] These estimates do not take into account the boundedness of the dependent variable. We distinguish the three time zones corresponding to Asian trading hours, European trading hours and US trading hours. We effectively assume that observations within time zones are correlated in an unknown way but that observations across time zones are uncorrelated. This allows us to take into account variations in liquidity over the trading day and across time zones, as discussed e.g. in Bollersev and Domowitz (1993) and Huang and Masulis (1999). Moreover, insofar as time zone distance is constant over time, its effect can no longer be estimated if we use OLS with fixed effects. This is why our baseline estimators are panel Tobit and GLM with random effects.

between 1995 and 2013, while submarine fiber-optic cables increased from a small handful to more than 300 in number.) This underscores the importance of controlling for unobserved country and time effects, as we do here.[29]

Our first control variable is distance. An interpretation of its effect is in terms of the costs of obtaining information or doing business to which it gives rise.[30] One mechanism is that traders outside the country of issuance face an information disadvantage and trade less profitably (Hau 2001). Onshore traders possess more and better information than offshore traders who are distant from local sources of public information, such as central banks, or private information, such as customer-order-flows (Menkhoff and Schmeling 2008).[31] Fiber optics level the playing field by cutting the cost of obtaining information from afar.

Specifically, time zone distance rather than physical distance is likely to matter for the location of information-intensive activities (see e.g. Bahar 2019). Non-overlapping trading hours increase the cost of doing business. Liquidity in the foreign exchange market varies significantly over the trading day and across time zones, being highest when European and US trading sessions overlap (see Bollersev and Domowitz 1993; Huang and Masulis 1999).[32] Moreover, prior to fiber-optics, traders in distant time zones did not receive news, market commentaries and buy and sell orders simultaneously, unlike traders in the same or adjoining time zones. Fiber optics help to relax barriers to information flows, data processing, and matching buy and sell orders arising from time zone differences.[33]

Our basic measure of distance, therefore, is time zones between the country issuing currency *i* and London, New York or Tokyo, whichever is closest to the country in question.[34] We expect that $\beta_1 < 0$.

Our second control variable is domestic market liquidity. More liquid markets allow transactions to be undertaken at lower cost. Buy and sell orders can be matched more easily. Bid-ask spreads are narrower, and traders can buy and sell larger blocks without moving prices. Where local markets are small and illiquid, agglomeration economies and thick-market advantages of offshore markets like London, New York or Tokyo known for their depth and liquidity will be particularly strong. Conversely, where local markets are liquid, they are likely to capture a larger share of trades.[35] Prior to fiber optics, traders in local markets could not easily seek liquidity elsewhere using traditional means, such as voicing trading. They could not easily match buy and sell orders with market participants trading from afar. With the advent of fiber optics, they can access a larger pool of quotes and match buy and sell orders with offshore traders more easily, reinforcing the thick-market advantages of major financial centers.

Our measure of domestic market liquidity is the volume of transactions in foreign currencies in country issuing currency *i* in year *t* (in USD trillion).[36] In the baseline model we exclude transactions in the domestic currency in order to avoid endogeneity with respect to the dependent variable. We anticipate that $\beta_2 < 0$; transactions in units issued by countries with relatively deep and liquid domestic financial markets tend to occur onshore.[37]

Our third control variable is restrictions on capital flows. The sign of the coefficient β_3 on this variable is ambiguous a priori. On the one hand, tighter capital controls bottle up transactions onshore. On the other hand they create incentives for the development of offshore markets, insofar as controls initially render the currency of the country in question scarce.[38]

[29] This point becomes evident if we regress domestic foreign exchange market turnover on cable connections. The coefficient on domestic turnover is positive and statistically significant when we do not control for country and time fixed effects. This might be interpreted as suggesting that cable connections may be associated with a higher volume of foreign exchange transactions in domestic financial centers. But when one controls for country fixed effects, the coefficient estimate becomes smaller. And adding time fixed effects, in order to strip out the effect of trends and of time-varying unobserved heterogeneity, turns the coefficient estimate *negative* and significant at the 11% level. This suggests that volumes in local financial centers in fact increased *less rapidly* than the global average after they were connected to fiber-optic cables, in line with the view that transactions moved to major financial centers and in line with our findings. Given the panel structure of our data set (55 currencies and 7 years) trended nature of the variables, including time and country fixed effects is appropriate – indeed essential.

[30] Such information asymmetries are key to exchange rate determination in the analysis of Bachetta and van Wincoop (2006) and to the vehicle role of a unit in the model of Lyons and Moore (2009).

[31] In contrast, the "financial center" hypothesis (Hau 2001) suggests that traders in large financial centers enjoy an information advantage. They have access to proprietary data bases and in-house research creating economies of scale and scope. They benefit from a larger customer base and better access to private information about order flows, which may also help them to forecast and exploit the trading interests of smaller traders (Moore and Payne 2011). They may reside in larger trading rooms and hence enjoy informational spillovers from colleagues trading, inter alia, fixed-income securities and equities.

[32] This matter for computer-run algorithmic or automated trading strategies seeking to transact with sleeping agents, this factor being emphasized in studies of the microstructure of the foreign exchange market such as in e.g. Bollersev and Domowitz (1993) and Huang and Masulis (1999).

[33] Contrasting the effects of physical distance with those of time zone distance provides a placebo test of the two mechanisms we have in mind. Insofar as fiber-optic connections affect the geography of FX trading mainly through higher bandwidth, they should not impact the effect of physical distance on the share of foreign exchange transactions occurring offshore to the same extent than time zone differences. The reason is that physical distance is correlated with latency but not bandwidth (the correlation is positive: the longer the cable between two geographical points, the higher the latency). Our estimates are consistent with this interpretation, as we show below.

[34] This means that there is one measure of distance relative to either London, New York or Tokyo per country. We use coordinated universal time, computed from the country's financial center time zone (New York for the US, Sydney for Australia, Shanghai for China, etc.) and take hour distance between London and Frankfurt for the euro. This choice is consequential: Johannesburg, for example, is more than 13,000 km away from London but only one time zone ahead.

[35] This can also be rationalized by referring to models in which concentration of an activity in a particular location has positive feedbacks on the advantages of further concentrating that activity in that location. See the models and arguments of Krugman and Venables (1995, 1996).

[36] We take the total volume of transactions in euro area members for the euro.

[37] In robustness checks, we also consider the logarithm of this variable, as well as the volume of transactions in all currencies (both foreign and domestic).

[38] Friedman (1969) argues that capital controls are equivalent in this context to a tax on purchases and sales of foreign currency. To evade this tax, residents then seek ways of accessing the currency, tax free, in a foreign venue. His example illustrating this hypothesis was the development of the Eurodollar market in London as a response to the adoption by the US of Regulation Q in the 1960s.

That controls encourage the development of offshore markets is widely argued by market participants (see e.g. HSBC 2011 and Credit Suisse 2013).[39] These markets develop through trading in non-deliverable forward contracts, which enable investors to trade claims indexed to a currency despite controls limiting their access to the underlying currency (McCauley, Shu and Ma 2014).[40] The advent of fiber optics further encourages traders to circumvent capital controls by lowering the costs of doing business with offshore traders.

As a measure of such restrictions, we use the time-varying indices of de jure capital account controls of (Fernández et al., 2015). These capture the overall importance of capital controls in country issuing currency i and in year t.[41] In robustness checks we separate controls on inflows and outflows.

In sensitivity tests, we control for other still variables whose omission could conceivably bias the results. These include trade openness (exports plus imports scaled by GDP, constructed from IMF data); financial openness (net external financial assets scaled by GDP, using updated data from Lane and Milesi-Ferretti 2007); a dummy variable for exchange rate flexibility which equals one if a country has a managed exchange rate or a float and zero otherwise, constructed using the updated classification of Ilzetzki, Reinhart and Rogoff (2019); and a metric of dollar-funded carry trades, namely the difference between the short-term local-currency interest rate on currency i and in year t and the corresponding US interest rate.[42]

Our baseline measure of *Cables* is a dummy variable that equals one if the country issuing currency i is connected directly or indirectly by a fiber-optic submarine cable to the UK, US or Japan (the three countries where matching servers of EBS and Thomson Reuters are located) and zero otherwise. In robustness checks, we consider point-to-point connections only, the number of separate cable connections and connections only to the UK, New York and Tokyo, respectively.

Our test of the effect of technology on the geography of the foreign exchange market considers the following null hypothesis:

$$H_0 : \gamma = 0 \text{ or } \forall j = 1, 2, 3,\ \varphi_j = 0$$

where j indicates one of the three interactions with cable connections in Eq. (1). Rejecting the null hypothesis suggests that technology has an impact on the geography of the foreign exchange market that can be direct, as captured by the coefficient γ, or indirect, i.e. via the interacted determinants of foreign exchange trading occurring offshore, as captured by the vector of coefficients $\boldsymbol{\varphi}$. The signs of γ and $\boldsymbol{\varphi}$ indicate whether a cable connection increases or reduces trading occurring offshore through its direct effect on the costs of trading and whether it dampens the impact of standard determinants such as distance, domestic market liquidity and capital controls on attracting foreign exchange trading onshore, as discussed above (i.e. we expect $\boldsymbol{\varphi}$ greater than 0). The net effect from the different coefficients indicate whether cable connections cause trading to move offshore to major financial centers or not.

7. Results

We first visualize our data before running regressions. Fig. 3 shows the average share of offshore foreign exchange transactions in the economies of the sample in 3-year intervals prior and after connection to the internet backbone (the length of the intervals corresponds to the number of years between waves of BIS triennial surveys). The share in question is stable – or falling – before connection. It then increases substantially in the interval immediately after connection, which suggests that fiber-optics tends to boost overall foreign exchange trading occurring offshore.

Table 1 reports estimates of equation (1) without the cable variables. Panel tobit estimates with random effects are in columns 1 and 2; panel GLM estimates in columns 3 and 4; linear panel estimates with random effects in columns 5 and 6; and pooled OLS estimates with country fixed effects in columns 7 and 8. Standard errors in columns 3 to 8 are robust to heteroscedasticity, while those in columns 5 to 8 are clustered by time zone. Time fixed effects are included throughout.

The results in column 1 suggest that the effect of distance on the share of trading offshore is negative and statistically significant, consistent with the "local information" hypothesis. The point estimate suggests that each hour difference relative to the US, the UK or Japan lowers the share of offshore trading of the currency issued by the country located in the time zone in question by 12 percentage points.

[39] For instance, entities that are not registered in China are not allowed to participate in onshore foreign exchange transactions of renminbi (also known as "CNY"), which must be executed via designated foreign exchange banks. Offshore entities can receive and pay renminbis to settle trade in goods transactions under certain conditions, however. This has contributed to the development of an offshore market of renminbis in Hong Kong (also known as "CNH") in the 2000s in which the renminbi can be freely transferred between accounts and across banks (although transfers to/from the mainland remain tightly regulated).

[40] Non-deliverable forwards are forward exchange agreements settled with a single US dollar payment. They hence allow market participants to obtain exposure to the underlying local unit without having to deliver it (unlike deliverable forwards). Transactions in non-deliverable forwards are included in the BIS data.

[41] The index of capital controls runs from zero (no controls) to one (full controls). For the euro we take the average of the index for the euro area members.

[42] We used money market rates (and Treasury bill rates when they are not available). In robustness checks we also obtained estimates using proxies of yen-funded carry trades, which gave similar results.

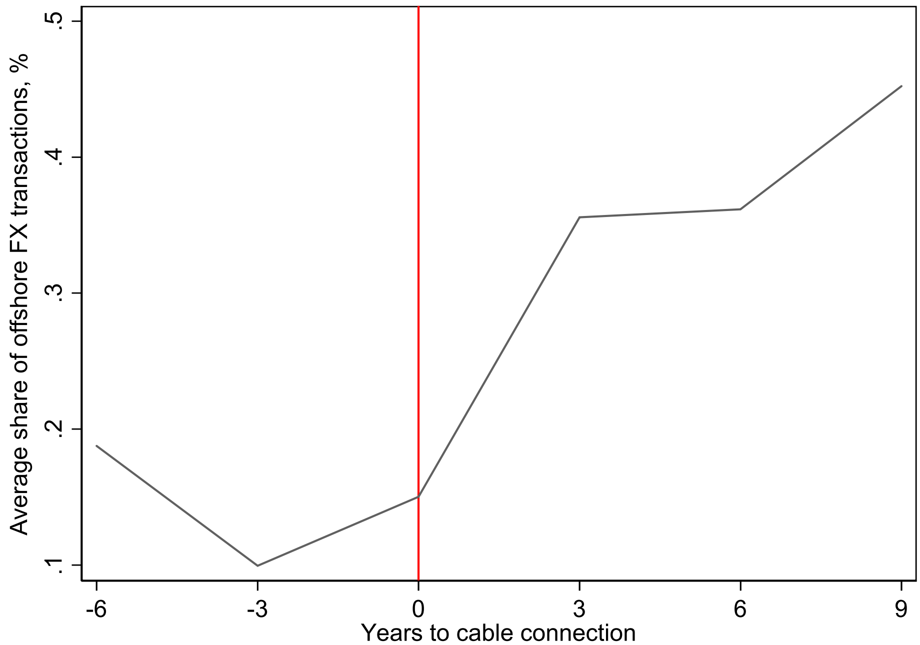

Fig. 3. Event Study of the Effect of Cable Connections *Notes*. This figure shows the average share of offshore foreign exchange transactions in the economies of the sample in 3-year intervals prior and after connection to the internet backbone (the length of the intervals corresponds to the number of years between waves of BIS triennial surveys).

Table 1
Estimates with Standard Determinants of the Location of FX trading.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel tobit	Panel tobit	Panel GLM	Panel GLM	Random effects	Random effects	Pooled OLS	Pooled OLS
Time zone distance	-0.120*	-0.085+	-0.257	-0.384+	-0.104***	-0.083*		
	(0.064)	(0.060)	(0.263)	(0.271)	(0.036)	(0.049)		
Domestic market	-	-	-	-	-0.299***	-0.303***	-0.345**	-
liquidity	0.383***	0.388***	1.384***	1.342***				0.346***
	(0.093)	(0.095)	(0.391)	(0.201)	(0.015)	(0.016)	(0.038)	(0.033)
Capital controls	-0.109	-0.100	-0.502	-0.525	-0.111**	-0.145***	-0.094	-0.152
	(0.107)	(0.106)	(0.466)	(0.476)	(0.045)	(0.054)	(0.123)	(0.112)
Trade integration		-0.091		-0.249		-0.067+		0.014
		(0.071)		(0.299)		(0.048)		(0.140)
Financial integration		0.094+		0.240		0.044		-0.005
		(0.060)		(0.281)		(0.045)		(0.102)
Flexible exchange rate regime		0.145**		0.765**		0.094***		0.028
		(0.056)		(0.341)		(0.033)		(0.034)
Carry trades		-0.005**		-0.032		-0.002		-0.002
		(0.002)		(0.045)		(0.002)		(0.003)
Constant	0.119	0.124	-1.331**	-1.150**	0.262***	0.275***		
	(0.100)	(0.110)	(0.547)	(0.568)	(0.047)	(0.005)		
Currency effects	YES	YES	YES	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES	YES	YES	YES
Observations	252	238	252	238	252	238	252	238
R^2					0.252	0.220	0.937	0.939
ρ	0.783	0.740			0.744	0.686		
Standard errors in parentheses								
*** p<0.01, ** p<0.05, * p<0.1, + p<0.2								

Notes. The table reports estimates of model equation (1) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading. Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in columns (3) and (4); linear panel estimates with random effects are reported in columns (5) and (6); and pooled OLS estimates with country fixed effects are reported in columns (7) and (8). The standard errors reported in parentheses in columns (3) to (7) are robust to heteroskedasticity and those in columns (5) to (8) are clustered by time zone (i.e. Asian, European, and US trading sessions); *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, The estimated effect of domestic market liquidity on offshore trading is similarly negative, as anticipated, and significant. The coefficient implies that the share of offshore trading of a currency issued by a country where the volume of local FX transactions is USD 250 billion larger (a large amount by today's standards) is about 10 percentage points lower.[43]

The effects of capital controls are more varied. The panel tobit. Panel GLM and pooled OLS estimates suggest that their effect is insignificant.[44] Recall that capital controls are likely to have two effects that are opposite in sign. Linear random-effects estimates in columns 5 and 6 suggest that the impact of controls is negative and significant. This suggests that the effect of capital controls in bottling up transactions at home dominates the opposing effect of encouraging the development of offshore markets in nondeliverables.

Estimates controlling for trade integration, financial integration, the exchange rate regime and carry trades are similar (see column 2 of Table 1), as are the panel GLM and linear panel random-effects estimates (in columns 3 to 6 of Table 1). The coefficient on exchange rate flexibility is positive and significant. The coefficient on carry trades is negative and also significant, which suggests that high local interest rates relative to the US encourage market participants to invest in local money markets and exchange funding in dollars, yen (or another low-interest rate unit) against local currency onshore to that end. The effect of capital controls is now more consistently negative than before.

Table 2 reports estimates where the share of foreign exchange trading taking place offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of a submarine fiber optic cable connection to the UK, the US or Japan.[45] The main findings of Table 1 remain broadly unchanged, with the estimated coefficients now being if anything larger in economic magnitude.[46] The unconditional effect of a cable connection is positive and statistically significant, confirming that fiber optics tend to boost overall foreign exchange trading occurring offshore (see column 1).

The mechanism becomes clearer with the conditional estimates (see columns 2 and 3). The conditional effect of a cable connection is negative and statistically significant, unlike the unconditional effect. This implies that a cable connection makes it more likely that a country will be able to retain or repatriate trading in its currency at home, other things being equal. An interpretation is that costs of trading locally are lower because local sales desks can now more efficiently communicate with the matching servers in offshore financial centers and access other internet-based applications, rendering them more competitive.

The interacted effects of submarine fiber optic connections, which operate through distance, domestic market liquidity and capital controls, are also statistically significant.[47] They tend to go in the opposite direction from the direct effect of fiber optic connections (they enter with a sign opposite to the sign of the connections variable when it is not interacted with the other determinants).

The results are similar with a panel GLM estimator (see columns 4 and 5). Overall, they suggest that the negative effect on the share of a currency traded offshore of distance is smaller (in absolute value) in the presence of a cable link. The negative effect of a relatively liquid local market is smaller (in absolute value) in the presence of cables. The negative effect of capital controls obtained from the linear random-effects estimates is again smaller in absolute value. Thus, where the direct effect of a cable link to one of the three major centers enables a country to retain more transactions in its currency onshore, the indirect effect is to weaken other factors (distance, local market liquidity, capital controls) that previously segmented markets and gave it a locational advantage.

Fig. 4 shows the predicted share of offshore FX trading conditional on time-zone distance when other spatial determinants are set to zero, both with cable connections (the solid line) and without (the dashed line).[48] The left-hand side is based on the tobit estimates reported in column 2 of Table 2; the right-hand side is based on the panel GLM estimates reported in column 4 of Table 2.

From the tobit estimates, the fact that a cable connection attenuates the effect of distance and local information is evident from the observation that the solid line (with cable) is flatter than the dashed line (without cable). For a country close to one of the financial centers, the main impact of the cable connection is direct; it allows the country to retain a larger share of trading in its currency (toward the left-hand side of the figure the solid line is below the dashed line, indicating that a smaller share of transactions occur offshore in the presence of a cable). South Korea, for example, is in the same time zone as Japan, where the Korean won is among the currencies least traded offshore. Conversely, for a country far from one of the financial centers, the main impact of the cable connection is indirect; it works to erode the advantages of distance, causing the country to lose a larger share of trading in its currency to offshore markets (toward the right-hand side of the figure, the solid line is

[43] Recall that domestic market liquidity is expressed in $trillion. $250 billion is not too far off the volume of offshore FX trading in Singapore or Zurich as of 2013. Readers will remember that we exclude here transactions in domestic currencies from the metric of domestic market liquidity to avoid spurious correlations. This result may possibly reflect agglomeration effects arising in a self-perpetrating way, as in Krugman and Venables (1995, 1996). It is also consistent with models emphasizing financial frictions, such as the limited risk-bearing capacity of financiers or international imbalances in the demand for financial assets, as in Gabaix and Maggiori (2015).

[44] He et al. (2015) analyze a smaller cross-section of currencies and a different specification, but they too find no statistically significant impact of capital controls.

[45] Both point-to-point connections and connections via third countries, recall, are considered here (in columns 2 and 3 respectively). Panel tobit estimates with random effects are reported in columns 1, 2 and 3; panel GLM estimates are in columns (4) and (5).

[46] As a result the negative effect of capital controls is also statistically significant at the 20% level of confidence.

[47] At the 20% level of confidence for capital controls.

[48] The time effects – which range from zero in 1998 and 70% in 2013 – are also set to zero.

Table 2
Basic Estimates – Impact of Submarine Cable Connections.

	(1)	(2)	(3)	(4)	(5)
	Panel tobit	Panel tobit	Panel tobit	Panel GLM	Panel GLM
Time zone distance	−0.117*	−0.463***	−0.430***	−1.443***	−1.586***
	(0.064)	(0.127)	(0.126)	(0.478)	(0.508)
Domestic market liquidity	−0.358***	−1.757**	−1.784**	−7.746***	−7.047***
	(0.093)	(0.818)	(0.831)	(2.115)	(1.827)
Capital controls	−0.111	−0.289+	−0.288+	−1.358+	−1.650**
	(0.106)	(0.186)	(0.190)	(0.845)	(0.794)
Cables	0.137**	−0.305***	−0.332***	−1.157**	−1.315***
	(0.065)	(0.114)	(0.115)	(0.518)	(0.483)
Cables × time zone distance		0.362***	0.361***	1.320***	1.294**
		(0.112)	(0.113)	(0.486)	(0.510)
Cables × domestic market liquidity		1.398*	1.415*	6.380***	5.677***
		(0.814)	(0.827)	(2.104)	(1.807)
Cables × capital controls		0.241+	0.243+	0.833	1.152+
		(0.189)	(0.192)	(0.892)	(0.858)
Trade integration			−0.079		−0.142
			(0.073)		(0.317)
Financial integration			0.095+		0.155
			(0.062)		(0.303)
Flexible exchange rate regime			0.128**		0.737**
			(0.054)		(0.346)
Carry trades			−0.004*		−0.026
			(0.002)		(0.034)
Constant	0.089	0.453***	0.463***	−0.159	0.016
	(0.101)	(0.133)	(0.142)	(0.431)	(0.565)
Currency effects	YES	YES	YES	YES	YES
Time effects	YES	YES	YES	YES	YES
Observations	252	252	238	252	238
R^2					
ρ	0.789	0.830	0.799		

Standard errors in parentheses
*** p < 0.01, ** p < 0.05, * p < 0.1, + p < 0.2

Notes. The table reports estimates of model equation (1) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of both point-to-point and via third countries submarine fiber-optic cable connections to the U.K., U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic trading are located). Panel tobit estimates with random effects are reported in columns (1) to (3); panel GLM estimates are reported in columns (4) and (5). The

above the dashed line, indicating that a larger share of transactions occur offshore). This is the case of New Zealand, which is three hours ahead of Japan and whose unit is heavily traded offshore.

At a distance of three hours, our tobit estimates suggest that the share of foreign exchange occurring offshore should be negative. The dependent variable is bounded between zero and one, which implies that quasi-linear estimates such as those obtained with tobit only approximate the true effects of the predictors around the dependent variable mean. Fitting the response variable with large predictor values hence may result in predicting expected shares outside the [0,1] domain, as it is the case here. This problem is familiar from other applications, such as in medical science and epidemiology, which has encouraged scholars to obtain panel generalized linear model (GLM) estimates with a logistic link function and a binomial distribution, as we do here (see Localio, Margolis and Berlin 2007; Diaz-Quijano 2012).[49] This approach allows the logistic transformation of the fitted response to vary linearly with the predictors while keeping the predicted share between zero and one. Consider now the right-hand side of Fig. 4. That a cable connection attenuates the effect of distance and local information over the relevant range is again evident from the fact that the solid curve (with cables) is flatter than the dashed curve (no cable).

The crossover point is at one hour. For countries in the same time zone as one of the three big financial centers, a cable connection is a positive for the market share of local sales desks. For countries two or more time zones away, the net effect on the local sales desk is negative.

How large is the effect on average? Taking the ratio in percentage terms of the slopes of the two lines obtained from the tobit estimates suggests that the effect of hour distance on the share of foreign exchange trading occurring offshore is 78 % lower on average in countries connected to a submarine fiber-optic cable relative to countries that are equally distant from a major financial center but not connected.[50]

[49] We also obtained very similar results with a probit link function in robustness checks.

[50] For the panel GLM estimates cable connection also reduces considerably the economic importance of distance, although the reduction rate is now nonlinear and varies with distance itself.

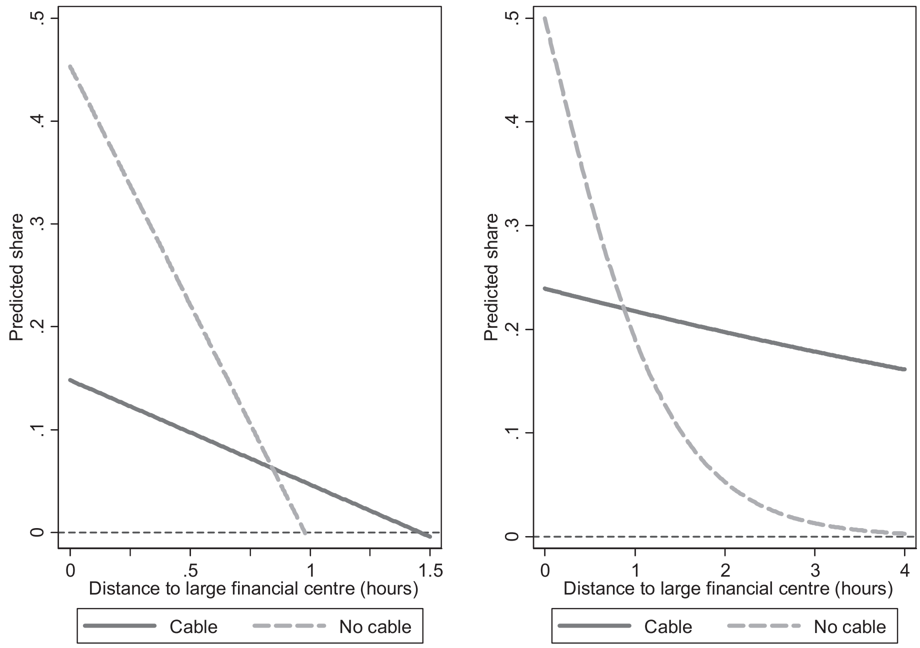

Fig. 4. Impact of Submarine Fiber-Optic Cable Connection – *Time Zone Distance Notes*. This figure shows the predicted share of offshore FX trading conditional on the extent of time zone distance, while other spatial determinants are set to zero with (solid line) and without (dashed line) cable connection. The left-hand side figure is based on the tobit estimates reported in column 2 of Table 2; the right-hand side figure is based on the panel GLM estimates reported in column 4 of Table 2.

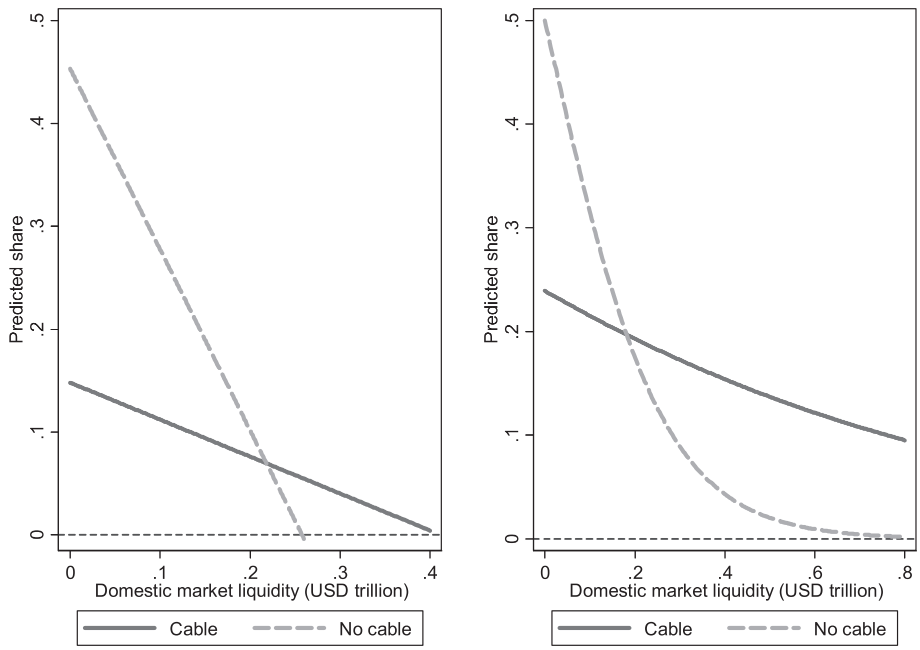

Fig. 5. Impact of Submarine Fiber-Optic Cable Connection – *Domestic Market Liquidity Notes*. This figure shows the predicted share of offshore FX trading conditional on the extent of domestic market liquidity, while other spatial determinants are set to zero, with (solid line) and without (dashed line) cable connection. The left-hand side figure is based on the tobit estimates reported in column 2 of Table 2; the right-hand side figure is based on the panel GLM estimates reported in column 4 of Table 2.

Fig. 5 shows how the attractions of deep and liquid domestic markets are lessened by cable connections, constructing predicted shares in the same manner. The solid line again is flatter than the dashed line. For a country whose domestic market is relatively illiquid, the direct impact of the cable, in leading to the retention or repatriation of business onshore, is the main effect. But a cable connection also attenuates the advantages of a highly liquid domestic market. Countries that previously saw a relatively high share of transactions in their currency occurring onshore due to domestic market liquidity may see a decline in that share with a cable connection. When Australia was connected in 2001, it saw the share of its currency trading offshore jump by seven percentage points in three years.[51]

Taking the ratio in percentage terms of the slopes of the two lines obtained from the tobit estimates suggests that the effect of domestic market liquidity on the share of foreign exchange trading occurring offshore is 80 % lower on average in countries connected to a submarine fiber-optic cable than in countries with equally liquid domestic markets but not possessing a cable connection.

Fig. 6 depicts the extent to which technology neutralizes the effect of capital controls.[52] Again the solid line is flatter than the dashed line, indicating that a cable connection attenuates the effect of controls.[53] A cable connection reduces the share of trading in a currency that occurs offshore through its direct effect; tighter controls would be expected to bottle up more of this business, but their impact is weakened by a cable connection, this being the cable's indirect effect. This time, however, the solid line is entirely below the dashed line due to the cable's direct effect.[54] But the effect of capital controls on the share of foreign exchange trading occurring offshore is still 83 % lower on average in countries connected to a submarine fiber optic cable relative to countries equally open financially but not connected in this manner.

8. Instrumental variables

As a robustness check, we use the ruggedness of the seabed and the 3-dimension length of the submarine fiber-optic cables as instruments for the existence of cable connections. Seabed ruggedness captures the existence of domes, canyons, faults, and other topological irregularities. Laying a cable between two points on the sea floor is more costly in the presence of such irregularities; they should therefore affect the location of cables and the timing of investments.[55] Insofar as irregularities arise from nature, they provide an exogenous source of variation. There is no other obvious reason why seabed ruggedness should affect the location of foreign exchange trading. This measure should therefore satisfy both the relevance and exclusion restrictions for a valid instrument.

Juhász and Steinwender (2018) show that ruggedness of the sea floor predicts when countries were connected to the telegraphic network in the 19th century.[56] In their spirit, we constructed the ruggedness instrument using a 30 arc-second grid of elevation for oceans data from the General Bathymetric Chart of the Oceans (GEBCO).[57] We computed the shortest undersea route between the two endpoints of the first undersea cable linking country i and the major financial center located in the closest time zone (i.e. London, New York or Tokyo).[58] We defined a 25 km buffer along both sides of the shortest route and computed the average ruggedness measure of Riley et al. (1999) within this buffer. The measure is defined as the square root of the sum of the squared differences in elevation between a point and its 8 neighbors in the major directions of the compass (i.e. north, northeast, east, southeast, south, southwest, west, and northwest).[59]

Our other instrument is the logarithm of the 3-dimensional (3-D) length of individual cables. This measure accounts for topological irregularities on the seabed along the shortest route, also tas in Juhász and Steinwender (2018).[60]

We consider each variable individually, jointly and their interaction as regressors in the first-stage where the dependent variable is the year when a country was connected to the internet backbone.[61] The F-statistic of the first-stage regression is over 12 when use 3-D cable length as instrument (see Table A3 in the online appendix), indicating more than adequate strength.[62]

When we use the year of connection predicted by the instruments in question – rounded to the nearest integer – in a second-stage regression, we obtain similar results as our basic estimates (see Table 3). Hence the dampening effect of cable

51 This occurred despite the fact that domestic market liquidity increased by 28% over the same period, something that should have worked in the other direction.

52 We do not report the panel GLM estimates here because the interaction between cable connection and capital controls was not statistically significant.

53 Intuitively-one might interpret this as cable communication opening up additional channels for evasion.

54 This is evident from Table 2, where the coefficient on capital controls interacted with cables is always smaller than the coefficient on controls, and the controls measure varies between zero and one.

55 These considerations are discussed by technical specialists; see e.g. Clark (2016) and Ye, Jiang, Pan and Jiang (2018).

56 Less directly related, Nunn and Paga (2012) show that the ruggedness of land in Africa has had positive effects on income insofar as rugged terrain afforded protection to those being raided during the slaves trade, which is thought to have retarded economic development.

57 At the equator, an arc-second of longitude approximately equals 1/60th of a nautical mile (or about 101 feet or 31 m). Arc-seconds of latitude remain nearly constant, while arc-seconds of longitude decrease in a trigonometric cosine-based fashion as one moves toward the earth's poles.

58 We used the aquaplot.com API to compute the routes in question on high-resolutions maps (e.g. allowing the shortest routes to go through narrow water paths, such as the Suez and Panama canals).

59 More formally, let $e_{r,c}$ denote elevation at the point located in row r and column c of a grid of elevation points; ruggedness at that point is computed as $\sqrt{\sum_{i=r-1}^{r+1}\sum_{i=c-1}^{c+1}(e_{i,j}-e_{r,c})^2}$. We then average across all grid cells along the route to obtain the average ruggedness measure.

60 Technical sources cited above support the notion that the longer the cable's length – in a 3-dimensional sense – the more technically difficult and costly is it to lay that cable on the seabed.

61 Figures A6 and A7 in the online appendix show that ruggedness and 3-D length are both correlated positively with the year of connection to the network of submarine fiber-optic cables, in line with our priors. The IV estimates exclude the two countries already possessing cable connections in 1989 insofar as our first-stage regression aims to predict year of cable connection over our sample period 1995–2013.

62 Power of the other instrument or combination of instruments is weaker, so we focus on 3-D cable length.

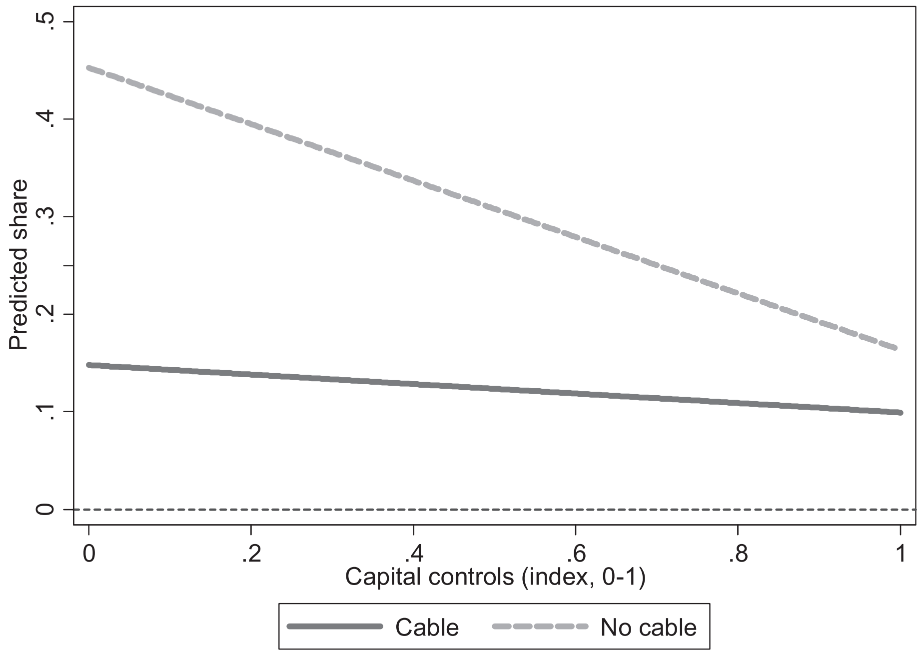

Fig. 6. Impact of Submarine Fiber-Optic Cable Connection – *Capital Controls Notes*. This figure shows the predicted share of offshore FX trading conditional on the extent of capital controls, while other spatial determinants are set to zero, with (solid line) and without (dashed line) cable connection. The figure is based on the tobit estimates reported in column 2 of Table 2.

connections on the standard gravity trade determinants is robust to the instrumental variable strategy and can be interpreted as causal.

9. Robustness

Table 4 reports further sensitivity checks, where we use a time trend in lieu of time fixed effects (column 1); cable connections interacted with a time trend (column 2)[63]; geographical distance instead of the time difference to the UK, US or Japan (column 3); the log of FX turnover rather than its level (column 4); total FX turnover rather than FX turnover net of domestic currency turnover (column 5); restrictions on capital inflows rather than restrictions on all flows (column 6); restrictions on capital outflows (column 7); and initial values of the standard determinants of the location of foreign exchange trading (column 8). Findings remain robust.

Table 4 also reports the results of a placebo test using physical distance in lieu of hour distance. The coefficients on physical distance and its interaction with fiber optic connections are statistically insignificant, in line with our earlier arguments. Column 7 then shows that the effect of technology on capital controls mainly goes through restrictions on outflows rather than inflows.[64]

The online appendix contains a battery of additional robustness checks. For example, we again find evidence of mitigating effects of fiber optic connections on the standard determinants of where currencies are traded when we restrict the estimates to shorter samples ending in 2010, 2007 or 2004 (Table A4 in the online appendix).

Conceivably, wider data coverage over time might affect our dependent variable and bias our estimates. We therefore estimated the same relationship on a balanced sample restricted to currencies reporting trading location since 1995. Although we lose half the observations, the estimates are unchanged in terms of sign, statistical significance and economic magnitude (Table A5 in the online appendix). Only the point estimates on capital controls and on its interaction with cable connections lose their previous statistical significance, possibly reflecting the loss in efficiency resulting from the smaller sample (Table A5).

We tested for parameter instability using Chow tests for structural breaks in 2001, 2004 and 2007. The results (columns 3 to 5 of Table A6 in the online appendix) show that changes in the interacted coefficients after the break tend to be insignif-

[63] We therefore control for the fact that our cable connection variable could just be picking up other global changes insofar as cable connectivity is positively correlated with time. And the results again suggest that our findings are not contaminated by unobserved global changes.

[64] We also examined bilateral data published by the BIS where we could look directly at offshore trading in London, Tokyo and New York for a small number of advanced economy units. However, their countries of issuance were almost all connected to the internet backbone simultaneously, implying that there was hardly any variation to exploit for identification.

Table 3
IV Estimates –3-D Cable Length Used as Instrument.

	(1)	(2)	(3)	(4)
	Panel tobit	Panel tobit	Panel GLM	Panel GLM
Time zone distance	−0.337***	−0.313**	−0.547***	−0.594***
	(0.129)	(0.129)	(0.205)	(0.213)
Domestic market liquidity	−1.577*	−1.594*	−4.072***	−4.067***
	(0.880)	(0.898)	(1.275)	(1.090)
Capital controls	−0.375+	−0.352+	−1.375*	−1.222+
	(0.241)	(0.235)	(0.801)	(0.750)
Cables	0.003	−0.047	−0.164	−0.334
	(0.140)	(0.142)	(0.307)	(0.311)
Cables × time zone distance	0.223*	0.231**	0.346+	0.386+
	(0.116)	(0.117)	(0.250)	(0.248)
Cables × domestic market liquidity	1.228+	1.237+	3.285***	3.248***
	(0.877)	(0.895)	(1.249)	(1.071)
Cables × capital controls	0.324+	0.309	1.068	0.905
	(0.251)	(0.246)	(0.872)	(0.801)
Trade integration		−0.068		−0.145
		(0.074)		(0.200)
Financial integration		0.083+		0.132
		(0.063)		(0.189)
Flexible exchange rate regime		0.114**		0.398**
		(0.054)		(0.198)
Carry trades		−0.004*		−0.013
		(0.002)		(0.014)
Constant	0.290**	0.309**	−0.341	−0.267
	(0.145)	(0.155)	(0.324)	(0.375)
Currency effects	YES	YES	YES	YES
Time effects	YES	YES	YES	YES
Observations	252	252	252	238
R^2				
ρ	0.833	0.833	0.808	

Standard errors in parentheses
*** p < 0.01, ** p < 0.05, * p < 0.1, + p < 0.2

Notes. The table reports estimates of model equation (1) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the predicted year when countries were connected to the internet backbone, using 3-D cable length as an instrumental variable. Panel tobit estimates with random effects are reported in columns (1) and (2); panel GLM estimates are reported in

icant statistically. Where they are significant, they point to slightly larger economic effects (the coefficient on the interaction between cable connections and time zone distance increases from about 0.3 to 0.4 for example).

We also controlled for time averages of the exogenous variables (Table A7 in the online appendix). While the averages are jointly significant, the estimated coefficients do not change in terms of sign, economic magnitude and statistical significance (columns 1 and 2 as well as columns 3 and 4 of Table A7). This suggests that even if our baseline estimates do not fully control for unobserved heterogeneity, any bias is small. In addition, pooled Tobit estimates with fixed effects are broadly in line with the basic estimates (columns 5 and 6 of Table A7).

We dropped observations from each year of the BIS triennial survey in turn to test whether our findings are driven by a particular year or years (Table A8 in the online appendix). The interacted coefficient on capital controls loses its statistical significance in some years. The interacted coefficient on domestic market liquidity loses its significance when we drop the observations for 1998 and 2010. Overall, however, the results remain robust.

We dropped individual countries from the sample one at a time to see whether the results were being driven by influential national cases. The estimates are robust (Table A9 in the online appendix). We re-estimated the key relationships controlling for offshore centers (i.e. countries on the list of non-cooperative jurisdictions designed by the IMF, OECD, the Financial Secrecy Index or other sources, such as the EU), taking data from Chiţu et al (2014). The results are unchanged (column 2 of Table A10 in the online appendix). We also tested whether the coefficients on cable connections were different for offshore centers than other countries, which is not the case (column 3 of Table A10). As we stress in the paper, undersea fiber optic cables have been laid mostly for reasons unrelated to trading; they were laid not because these islands are tax heavens but, rather, because they have favorable seabed topology.

We split cable connections into connections to London only, New York only, and Tokyo only. The results are robust (see Table A11 in the online appendix).

We also explored potential nonlinearities in the role of capital flow restrictions. We asked whether the coefficients on the cable variables were different for countries with stricter capital controls relative to other countries using binary dummies which equal one if a country is among the top-30 %, 20 % and 10 %, respectively, of the capital control distribution in a given year, and zero otherwise. This is not the case (see Table A12 in the online appendix).

Table 4
Robustness Checks.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Time trend	Cables × time trend	Geo distance	Log turnover	Total turnover	Capital inflows	Capital outflows	Initial determinants
Time zone distance	−0.405***	−0.401***	−0.058**	−0.450***	−0.476***	−0.453***	−0.432***	−0.375***
	(0.110)	(0.109)	(0.023)	(0.129)	(0.132)	(0.132)	(0.122)	(0.122)
Domestic market liquidity	−1.727**	−2.603***	−1.639*	−2.193**	−1.273**	−1.902**	−1.711**	−0.389***
	(0.834)	(0.972)	(0.868)	(0.907)	(0.622)	(0.845)	(0.832)	(0.091)
Capital controls	−0.469***	−0.577***	−0.265+	−0.280+	−0.289+	−0.232	−0.208+	−0.014
	(0.180)	(0.201)	(0.206)	(0.187)	(0.187)	(0.275)	(0.128)	(0.119)
Cables	−0.332***	−0.282***	−0.064	−0.331***	−0.374***	−0.326***	−0.327***	−0.281**
	(0.101)	(0.103)	(0.094)	(0.115)	(0.123)	(0.120)	(0.113)	(0.111)
Cables × time zone distance	0.333***	0.342***	0.020	0.366***	0.392***	0.390***	0.358***	0.378***
	(0.093)	(0.093)	(0.017)	(0.114)	(0.119)	(0.119)	(0.108)	(0.112)
Cables × domestic market liquidity	1.357+	2.257**	1.265+	1.353+	0.911+	1.538*	1.339+	0.809+
	(0.829)	(0.974)	(0.864)	(0.894)	(0.616)	(0.840)	(0.828)	(0.558)
Cables × capital controls	0.454**	0.561***	0.229	0.230	0.247+	0.164	0.195+	−0.077
	(0.179)	(0.198)	(0.210)	(0.190)	(0.190)	(0.277)	(0.133)	(0.158)
Trade integration	−0.054	−0.103+	−0.116+	−0.071	−0.078	−0.085	−0.074	−0.142**
	(0.074)	(0.077)	(0.072)	(0.073)	(0.073)	(0.073)	(0.072)	(0.069)
Financial integration	0.085+	0.125*	0.115*	0.098+	0.081+	0.099+	0.090+	0.093+
	(0.063)	(0.067)	(0.060)	(0.062)	(0.062)	(0.063)	(0.062)	(0.062)
Flexible exchange rate regime	0.112**	0.119**	0.161***	0.121**	0.125**	0.126**	0.129**	0.124**
	(0.054)	(0.055)	(0.058)	(0.054)	(0.053)	(0.055)	(0.054)	(0.063)
Carry trades	−0.003+	−0.004+	−0.004*	−0.004*	−0.004*	−0.004*	−0.004*	−0.027***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.006)
Constant	0.283**	0.274**	0.210*	0.479***	0.506***	0.477***	0.447***	0.460***
	(0.137)	(0.135)	(0.111)	(0.145)	(0.150)	(0.145)	(0.141)	(0.136)
Currency effects	YES	YES	YES	YES	YES	YES	YES	YES
Time effects	NO	NO	YES	YES	YES	YES	YES	YES
Observations	238	238	238	238	238	238	238	203
ρ	0.792	0.782	0.739	0.822	0.821	0.799	0.802	0.766

Standard errors in parentheses
*** p < 0.01, ** p < 0.05, * p < 0.1, + p < 0.2

Notes. The table reports estimates of model equation (1) where the share of foreign exchange trading occurring offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of both point-to-point and via third countries submarine fiber-optic cable connections to the U.K., U.S. or Japan (i.e. the three countries where the matching servers of EBS/Reuters for electronic trading are located) and a time trend in lieu of time fixed effects (in column 1); cable connections interacted with a time trend (in column 2); geographical distance in lieu of the time difference to the U.K., U.S. or Japan (in column 3); the log of FX turnover rather than its level (in column 4); total FX turnover rather than FX turnover net of domestic currency turnover (in column 5); restrictions on capital inflows rather than restrictions on all flows (in column 6); restrictions on capital outflows (in column 7); initial values of the standard determinants of the geography of foreign exchange trading (in column 8). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, + $p < 0.2$.

We estimated whether the coefficients on the cable variables were different for major currencies, using binary dummies which equal one if a currency is a global reserve unit (US dollar, euro, yen, Swiss franc and pound sterling) or among the G10 units (the same currencies along with the Norwegian krone, the Swedish krona, the Australian, New Zealand and Canadian dollars). This is not the case insofar as the interacted coefficients are mainly insignificant, with the exception of the one on capital controls (Table A13 in the online appendix).

Table A14 in the online appendix reports estimates when the share of foreign exchange traded offshore is regressed on the standard determinants of the geography of foreign exchange trading as well as the direct and interacted effect of exclusively point-to-point submarine fiber-optic cable connections with the UK, US and Japan (as opposed to including also cable connections to the UK, US and Japan via third countries).[65] Results remain broadly unchanged in terms of sign, statistical significance and economic magnitude.[66] Table A15 in the online appendix then reports the estimates when we use the number of connections to submarine fiber-optic cables as our measure of technology. Again our main results are broadly unchanged.[67]

10. Competition among financial centers

Finally, we inquire into the impact of cable connections on the location of foreign exchange trading among the world's financial centers.

Changes to the location of global foreign exchange trading matters for welfare for several reasons. It may lead to transfers of factor of production (labor and capital) to where business is re-located offshore to be conducted more efficiently. Relocation of financial services has a direct impact on the development of cities and the regional distribution of employment and income (Gehrig, 1998). Moreover, financial centers tend to benefit disproportionately in employment and tax revenues (Tschoegl 1989). Brexit has shown that these effects can be material: about 400 financial firms and asset worth about USD 1.4 trillion had been relocated away from the UK in 2021.

Fiber-optic cable connections with major financial centers increase the number of varieties (currencies) transacted by traders, thereby improving welfare of market participants both onshore and offshore (Krugman, 1980). For instance, prior to South Africa's connection to the internet backbone in 2001, traders could only trade the rand against few currencies, such as sterling and the dollar. After activity started to move to London, New York and other financial centers in 2001, liquidity increased, and this expanded the number of currencies against which the rand could be traded without using sterling or the dollar as vehicle units.

A related point is that relocation of foreign exchange transactions to major financial centers makes trading more efficient, further enhancing welfare. Kindleberger (1974) pointed out that centralization of trading in a single center reduces transaction costs: in the case of n financial centers trading each in one currency, $n - 1$ transactions are required in lieu of $n(n-1)/2$ bilateral transactions. Another channel of efficiency gains is information spillovers. The presence of other financial market participants stimulate communication. More information and ideas can be exchanged and put to productive use, which is important for assets with complex payoff structures (Gehrig, 1998; Gehring 1998; Glaeser and Cutler, 2021).

Yet another implication concerns risk-averse traders benefitting from higher market liquidity and lower risks of large price changes due to shocks. Pagano (1989) shows that the expected utility of risk averse traders increases when there are more traders in the market, provided that liquidity shocks are not perfectly correlated.

Finally, connecting to global markets can improve risk sharing and increase welfare further as a result. Because transaction costs are lower in integrated markets, traders can build forex portfolios with a broader pool of currencies. They can rebalance their holdings and net out positions at lower cost, and in turn hedge more easily against exchange rate shocks.

These welfare gains need to be balanced against potential losses arising from concentration of foreign exchange activity in a few financial centers. (Gehrig, 1998) notes that it is less efficient to trade from abroad assets that are highly sensitive to local information. (Stocks, as he puts it, is an example of such assets, hence explaining home equity bias.) Costs may increase because of congestion and competition for scarce factors of production (e.g. labour, land, internet broadband, etc.) which send their prices soaring. Factor mobility (e.g. labour migration) or technological improvements (e.g. moving from 4G to 5G) might reduce such congestion costs and ease price pressures over time. But the price of immobile inputs and resources available in fixed supply, such as land, permanently increase, as stretched property prices in e.g. London, New York or Hong Kong testify.

We estimate the net impact of cable connections on the share of offshore foreign exchange transactions using the panel GLM estimated coefficients in column 4 of Table 2. We also predict shares under a counterfactual where issuing countries are not cable-connected (i.e. by setting the coefficient γ and those in vector $\boldsymbol{\varphi}$ to zero). The difference between the predicted and estimated counterfactual shares is the net effect of cable connections in percentage points by currency. The net effect is converted into transaction volumes using actual turnover for each currency.

The results are shown in Fig. 7 based on 2013 data. The dampening effect of cable connections on spatial determinants generally dominates the reduction in the costs of trading currencies locally in net terms; the share of offshore trading is

[65] Convergence of the panel GLM estimates were here obtained with a probit (rather than logit) link function.

[66] The exception is the effect on capital controls, which loses statistical significance.

[67] The exception is again the effect on capital controls, which loses statistical significance. Note also that the estimated coefficients on the interacted effects are smaller in economic magnitude, which is due the fact that our measure of technology is a continuous variable rather than a binary dummy as in Tables 2 and 3. Convergence of the panel GLM estimates with the additional controls was not obtained.

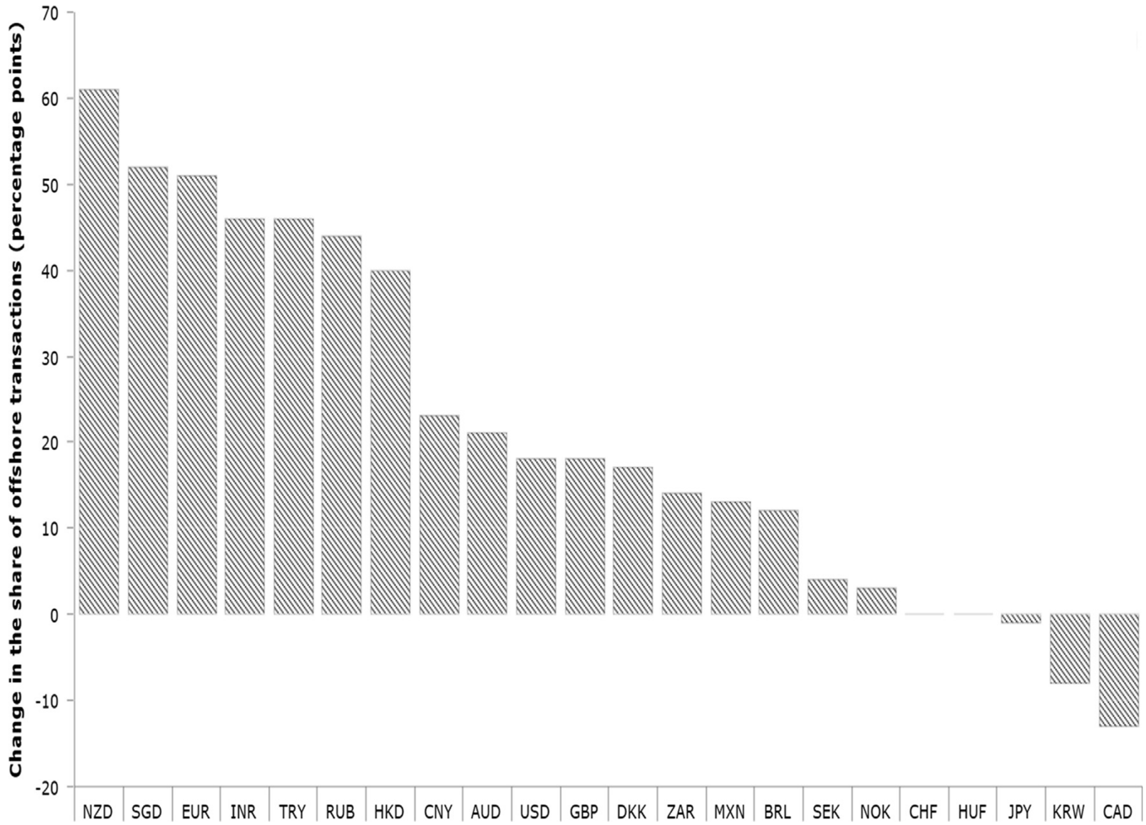

Fig. 7. Net Effect of Cable Connections on Offshore FX trading *Notes*. This figure shows the change (in percentage points) in the share of foreign exchange transactions occurring offshore by currency if countries which issue the currencies in question are connected to a submarine fiber-optic cable relative to a counterfactual situation when they are not. These estimates are based on data for 2013 and the GLM results reported in column 4 of Table 2.

higher for most units. The cross-currency average suggests that cable connections increase, in net terms, the share of offshore trading by about 21 percentage points.

The Canadian dollar, whose offshore share declines by 10 percentage points, is an exception. This is intuitive: Toronto is in the same time zone as New York, the Canadian forex market is relatively thin, and Canada is open financially. There are few spatial determinants to attenuate, in other words, so only the reduction in the costs of trading locally remains. A similar story pertains to the Korean won.

The New Zealand dollar and Indian rupee are contrary cases: their offshore shares increase by about 50 percentage points. These units are issued by the two countries most remote from the major financial centers. Hence the dampening effect of cable connections on distance is substantial.[68]

The shares of the US dollar, the euro and sterling also increase substantially, similarly reflecting the mitigating effects of cable connections on distance and on the attractions of their large and liquid local foreign exchange markets. The shares of the Swiss franc and Hungarian forint, in contrast, do not change, which is again intuitive: Switzerland and Hungary are land-locked and have no submarine fiber-optic cable connections.

In the second step, we allocate net gains and losses in the volume of offshore trading by currency between financial centers. We have total net volume estimates by currency.[69] We therefore allocate the counterfactual offshore trading volumes across financial centers proportionately to their actual shares in global foreign exchange turnover in 2013. Thus, if the UK accounts for 42 % of global foreign exchange turnover, it receives 42 % of the counterfactual net gains in the volume of offshore trading by currency.[70]

Fig. 8 shows the net percentage point change in the share of global foreign exchange turnover by country. The main losers from cable connectivity are Frankfurt and other euro area financial centers and, perhaps surprisingly, New York, with losses

[68] New Zealand is three hours ahead of Tokyo while India is four hours behind.

[69] Unfortunately, we are not able to split these estimates by both currency and financial center. In other words, we know by how much trading volumes move offshore, but we do not know exactly to where.

[70] Onshore trading volumes in the currency in question are reduced accordingly so that global turnover remains unchanged. A more extreme assumption would be to allocate net gains only to London, New York and Tokyo (i.e. to consider only point-to-point connections rather than also indirect connections). But that would only magnify the sizeable boost to the global market share of London and Tokyo which we document below.

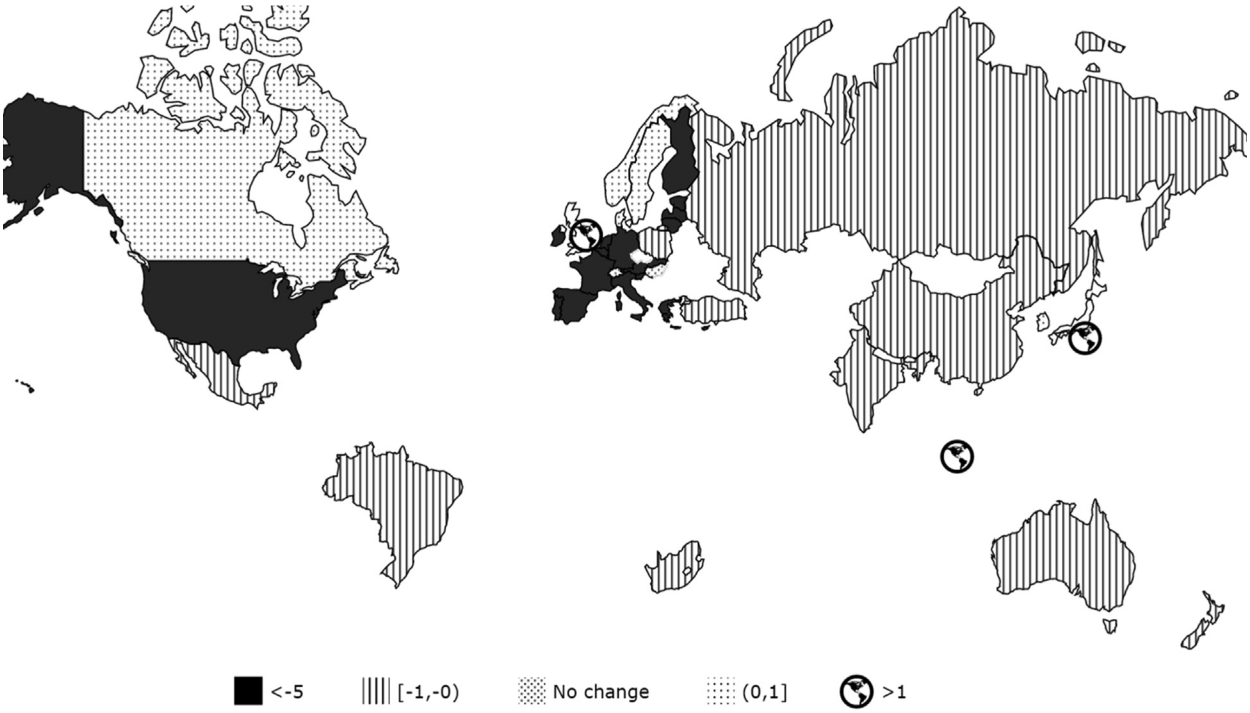

Fig. 8. Distributional Effects of Cable Connections Across Financial Centers *Notes*. This map shows the change in percentage points in the share of global foreign exchange transactions undertaken in the countries of our sample if they are connected to a submarine fiber-optic cable relative to a counterfactual in which they are not. The estimates are based on data for 2013 and the panel GLM results reported in column 4 of Table 2. They are based on the assumption that net gains in offshore trading (i.e. the balance between the direct and indirect effects of cable connections) are allocated across connected countries proportionately to their actual share of global foreign exchange transactions in 2013.

of seven and five percentage points of global foreign exchange turnover, respectively. Cable connections cause transactions in the dollar and euro to move offshore, i.e. away from New York and Frankfurt but in addition lead to the geographical redistribution of a relatively large *volume* of foreign exchange transactions, insofar as the dollar and the euro are two of the principal currencies traded in foreign exchange markets. The volume of transactions in other currencies that move *to* Frankfurt and New York from other financial centers, in contrast, is much smaller.

An overall winner is the UK, with a gain of 10 percentage points of global foreign exchange turnover due to cable connectivity. Other centers affected positively include Japan and Singapore, with gains of about one percentage point each. While London, Tokyo and Singapore are all major financial centers for foreign exchange trading, their own currencies are not traded as heavily as the euro and the dollar. Thus, what London, Tokyo and Singapore lose when trading in their respective units moves offshore is more than compensated for by the trading in other units that cables allow them to attract from other financial centers.[71] That the winners are islands (or a peninsula in the case of Singapore) is a reminder that the advantages afforded by cable connections have deep geographical roots, which underscores their exogeneity.

These changes are economically important. The increase of 10 percentage points of the share of London in global foreign exchange turnover is equivalent to a one-third increase relative to the counterfactual when it has no cable connections. In contrast, Switzerland's share stays constant since it has no submarine cable connection.

11. Conclusion

Using data on 55 currencies between 1995 and 2013 and the inauguration of submarine fiber-optic cables as a source of exogenous technological change, we estimate the impact of cable connections on the share of offshore foreign exchange transactions. We find that the dampening effect of cable connections on spatial determinants dominates the reduction in the costs of trading currencies locally. Cable connections increase the share of offshore trading.

The dampening effect of cable connections on the standard gravity trade determinants is robust to an instrumental variable strategy using the 3-dimension length of the submarine fiber-optic cables as an instrument. It is robust to other checks. Our estimates suggest that technology dampens the impact of spatial determinants by up to 80 percent and increases the share of offshore trading by an average 21 percentage points. It has economically important implications for the distribution

[71] An additional explanation in the case of the yen is that the net effect of cable connection is to increase the share of onshore trading.

of foreign exchange transactions across financial centers, boosting e.g. the share in global turnover of London, the world's largest trading venue, by an estimated one-third.

Data availability

The authors do not have permission to share data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We analyze the impact of technology on the production and trade in services.

We are grateful to the associate editor (Kasper Roszbach), two anonymous referees, Mark Aguiar, Pol Antràs, Thorsten Beck, Geert Bekaert, Bruno Biais, Jérôme Busca, Estelle Cantillon, Giancarlo Corsetti, Alexander Duering, Torsten Ehlers, Benoît Geller, Jérôme Héricourt, Jean Imbs, Takatoshi Ito, Amit Khandelwal, Philip Lane, Istvan Mak, Guy-Charles Marhic, Philippe Martin, Martin Uribe, Frank Packer, Hashem Pesaran, Romain Rancière, Andrew Rose, Alan Taylor and Xavier Vives for comments and discussions, as well as to seminar participants at the ECB, Goethe University Frankfurt and USC Dornsife and to participants at the Clausen Center Conference on Global Economic Issues, Berkeley, and to the Cambridge-INET conference on the microstructure of the FX market for comments. We thank Ziqi Li for excellent research assistance. We are also grateful to Denis Pêtre and Philip Wooldridge for providing unpublished Bank for International Settlements data on offshore foreign exchange trading. The views expressed are those of the authors and do not necessarily reflect those of the ECB, the Eurosystem or the IMF.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jimonfin.2023.102802.

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