Collateral Demand in Wholesale Funding Markets[*]

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Repo markets are systemically important funding markets, but are also used by firms to obtain the assets provided as collateral. We build and structurally estimate a model of trade between heterogeneous firms in the sterling gilt repo market, and show that this collateral demand depresses repo market activity and can impede the transmission of monetary policy. We quantify how well designed central bank repo facilities can improve outcomes: if the central bank were to lend out the assets on its balance sheet following quantitative easing, transmission and total firm surplus would improve by 17% and 50%, respectively.

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1 Introduction

Repurchase agreements (repo) temporarily exchange cash for collateral and serve three important functions. First, the repo market is the single most important source of wholesale funding for a broad range of financial firms (funding demand). Second, it is a key means of obtaining assets: the firm lending cash may trade to temporarily obtain the asset offered as collateral (collateral demand), including to short it. Third, the repo market also serves as the first point of contact for monetary policy.

Outcomes in repo markets are thus important for financial stability, asset prices and the transmission of monetary policy. The complication is that, naturally, these are equilibrium outcomes over which policymakers have only imperfect control. In particular, there is increasing evidence that collateral demand is an important, but unpredictable, driver of these outcomes. Changes in collateral demand have impeded the transmission of monetary policy (Nguyen et al., 2023) and led to segmentation in rates across firms (Schaffner et al., 2019). There is evidence that some of these changes in collateral demand occur because central bank asset purchases lead to a shortage of available assets (Nguyen et al., 2023). In this context, there is a live policy debate about how central banks should manage their balance sheets and how they should structure the repo facilities in which they transact with dealers and banks.

In this paper we study the interplay between policy, funding demand and, in particular, collateral demand, and seek to answer the following questions. First, measurement: how should collateral demand be measured and how does it vary across firms and time? Second, equilibrium effects: what is the effect of this collateral demand on outcomes in the repo market, both in normal times and in a stress? Third, policy: what does collateral demand mean for monetary policy transmission and the design of central bank repo facilities?

We answer these questions based on two innovations. We use detailed transaction data on the Sterling gilt repo market[1] and document new empirical facts on how collateral demand varies across firms. We then set out and structurally estimate a novel model of repo trading in which firms are heterogeneous in their funding needs and their collateral demand, with central bank repo facilities. This is, to our knowledge, the first structural model of collateral demand or specialness.[2]

We then use this estimated model to address the questions we set out above. On measurement, the model allows us to extract granular estimates of firms' collateral demands from the observed joint distribution of repo market rates and trading quantities. We find that dealers have heterogeneous but material collateral demand, particularly in times of high interest rate volatility. On equilibrium effects, we show that collateral demand *depresses* repo market activity: if collateral demand were counterfactually removed from repo markets, quantities and realised gains from trade would increase. This surprising result is driven by the joint distribution of preferences across firms that we structurally estimate: the firms that need funding in relative terms are also those that care more about the underlying collateral, which limits gains to trade. On policy, we quantify how surplus, segmentation and monetary policy transmission would all improve if the central bank were to lend out the assets it has on its balance sheet in repo markets. However, substantial segmentation and impaired transmission would remain, suggesting that other important drivers of collateral demand remain in addition to central bank purchases.

The starting point for our work is transaction data on close to the universe of repo lending and borrowing backed by UK government bonds, from January 2017 to March 2023. It is well-established that collateral demand exists, can be material, varies across assets, time and countries, and responds to monetary policy (Arrata et al., 2020; Mancini et al., 2016;

[1]The repo market using UK government bonds (gilts) as collateral.

[2]A bond with material collateral demand in repo markets is referred to as a special Duffie (1996).

Roh, 2019; Schaffner et al., 2019). Our data include a complete set of firm identifiers, and so allow us to study the distribution of collateral demand *across firms*, which is a key driver of gains to trade and the resulting equilibrium outcomes. In our first set of empirical facts, we show that there is substantial heterogeneity in collateral demand across firms. We show, for example, that hedge funds charge lower interest rates when lending than money market funds, whose mandates limit their incentive to demand specific bonds as collateral, and these rates are much more sensitive to the precise bond chosen as collateral.

In our second set of empirical facts, we unpack this heterogeneity and study the joint distribution of collateral and funding demand. We show that some firms are simultaneously net *borrowers* against general collateral, but net *lenders* against specific collateral. This is true even when the rate that they receive when lending is significantly worse than the rate they pay when borrowing. In other words, these firms that need cash also clearly need specific types of collateral. We then compare the rate at which a given firm trades general collateral and the discount at which it trades specific collateral, and show that the two are positively correlated: firms that value cash also appear to value specific collateral. In sum, it is not the case that the repo market simply matches firms that want cash with firms that want collateral, but instead individual firms seek to simultaneously manage their cash and collateral needs.

To understand how this distribution of preferences across firms matters for equilibrium outcomes, we build a model. Repo in the model is a temporary exchange of cash for an asset. Firms use the cash they obtain to fund a risky project, but also use the assets they obtain as collateral to obtain a risky return (from shorting the asset, for example). There are multiple assets, representing each of the bonds that can be used as collateral, and the firms simultaneously write repos against any of these assets. There are two types of firms, dealers and customers, connected by an exogenous trading network that governs the set of customers with which each dealer can trade. Dealers also have access to a competitive inter-dealer market. Beyond their type and position in the network, firms are heterogeneous in the expected return they earn from cash (their funding demand) and the expected return they earn from each of the different types of collateral (their collateral demand).

The model pins down a unique equilibrium in which a firm's portfolio choices - its repo borrowing and lending against each asset - depend on its demands for cash and collateral, and those of its counterparties. Collateral demand increases the payoff to borrowing (as the borrower obtains valuable collateral), but decreases the payoff to lending. The net effect of collateral demand on volumes and gains to trade can thus be positive or negative depending on which effect dominates. If collateral demand is negatively correlated with funding demand, then the additional payoff to lenders (that typically have low funding demand) dominates the reduced payoff to borrowers. In this case, collateral demand increases trading volumes and gains to trade. If instead the two are positively correlated, then the reverse is true and collateral demand reduces trading volumes and gains to trade. The effect of collateral demand thus depends on the joint distribution of collateral and funding demand across firms, which is exactly what our data are well suited to measure.

We then return to the data to structurally estimate our model. Our objective is to use our model and the transaction data to recover the joint distribution of funding demand and collateral demand across firms, assets and time as flexibly as possible. The model is designed to offer tractable linear estimating equations that allow us to do this, while respecting various important institutional features. The estimation also recovers the curvature parameters in the model that govern the sensitivity of trading quantities to rates.

We use this estimated model to answer the research questions that we set out above on measurement, equilibrium effects and policy implications.

Having recovered these estimates of collateral demand from our structural estimation, we interrogate its variation over time, firms and assets, and reach three initial findings. First, we uncover the different drivers of collateral demand and funding demand over time: funding demand closely follows the UK's monetary policy stance, whereas collateral demand co-moves closely with forward implied volatility in secondary bond markets. Second, we find that collateral demand varies significantly across firms, and is not limited to hedge funds seeking to speculate. Dealers and hedge funds have particularly high collateral demand, whereas mutual funds, money market funds and pension funds have relatively low collateral demand. Collateral demand and funding demand are positively correlated across firms, indicating that those firms that need funding also care more about the specific collateral being exchanged. Third, collateral demand covaries with asset characteristics representing its desirability and the ease of sourcing it in repo markets.

We then turn to the equilibrium effect of collateral demand. We simulate a counterfactual equilibrium in which we remove any collateral demand, so as to quantify exactly how collateral demand affects repo market functioning. In practice, given our estimation procedure, this counterfactual asks what would happen if all market participants valued specific collateral the way they currently value general collateral. We find that quantities and realized gains from trade in repo markets would increase in this counterfactual, very materially so in periods of financial stress when estimated collateral demand was high. This result is surprising, as previous work (Singh, 2011) has suggested collateral demand lubricates repo market activity, when we find instead that collateral demand depresses repo market activity.

This result is not due to any friction or inefficiency, but is due to the distribution of preferences across firms that we recover from our structural estimation, and in particular the fact that funding demand and collateral demand are positively correlated across firms. This suggests that the gains to trade to a repo transaction that exchanges funding for collateral are limited. We unpack this in further counterfactual simulations, in which we show that

(1) this is driven primarily by the preferences of dealer and banks and (2) the counterfactual results would reverse if funding and collateral demands were instead negatively correlated across firms.

Finally, we turn to policy, and study the effect of central bank repo facilities on monetary policy transmission and surplus. We find that changes in the central bank's base rate change firms' funding demand, which is then transmitted on to the equilibrium repo rate. Changes in collateral demand around this time also affect this equilibrium rate, and so can dampen or amplify this transmission. Duffie and Krishnamurthy (2016) show that a central bank reverse repo facility[3] can improve transmission by acting as a floor on repo rates (or equivalently as a ceiling on specialness). Intuitively, if the central bank supplies bonds that are in demand then this mitigates the effect of changes in collateral demand on equilibrium repo rates.

There is no central bank reverse repo facility in the UK, but we extend our model to include one and simulate its effects. The usage and effect of such a facility depend on (1) collateral demand, and whether that makes the rate offered by the central bank facility attractive, and (2) the sensitivity of trading quantities to rates, which is exactly what our model and estimation are designed to capture.

We find that in principle a reverse repo facility that is unconstrained in what it can lend out and is priced at 35bps below the base rate would improve monetary policy transmission by 40% on average. A facility priced at 5bps below the base rate would improve transmission by 90%. This would involve, however, the central bank lending extremely large volumes of bonds: collateral demand is sufficiently high that supporting such a floor on repo rates would involve the central bank lending far more government bonds than it has on its balance sheet. We thus go on to study a constrained reverse repo facility that cannot lend out more than the central bank (the Bank of England, in our case) has on its balance sheet following

[3] In a reverse repo facility the central bank takes cash and lends out assets.

quantitative easing: such a facility priced at 5bps (35bps) under the base rate would improve transmission by 17% (9%). The usage and effects of these facilities are state-dependent, and much lower when collateral demand is low and the floor on rates they impose does not bind (as would mostly have been the case prior to 2022 in our sample, for example).

Turning to the effect on surplus, we show that such a facility would have improved surplus very significantly - by between 50% and 270% depending on how exactly surplus is calculated - as it transfers assets from the central bank (who do not make temporary use of these assets and have no collateral demand) to market participants (who would have). We also simulate a central bank collateral swap facility, and find that it would improve surplus and reduce segmentation across assets, but not transmission.[4]

These results are important for two reasons. First, because they speak to a live policy debate about whether central banks should lend out the assets they own: the Federal Reserve and the European Central Bank both have securities lending programs, whereas the Bank of England does not. We give a direct, quantitative answer to how this would affect transmission and surplus, and how the design and pricing of the facility matters. Second, because they speak to the causes of specialness, and confirm that, while central bank purchases are a key driver of specialness and thus of impaired transmission, they are not the only one. Substantial collateral demand and impaired transmission would remain even in the presence of such facilities. More generally, policy-making in this market requires joint consideration of both conventional and unconventional monetary policy, as well as the specific design of central bank repo facilities.

[4]Banks can use this central bank swap facility to exchange gilts. Unlike a reverse repo facility, it does not change the total volume of gilts available to banks, which is why we find that it would not improve transmission.

1.1 Related literature

Our primary contribution is to the empirical literature on repo markets. Important papers in this literature include Copeland et al. (2014); Gorton and Metrick (2012); Hu et al. (2021); Krishnamurthy et al. (2014) on the US repo market and Mancini et al. (2016) and Boissel et al. (2017) on European repo markets. Within this growing field, we contribute to three specific strands.

The first strand studies the role of collateral demand in the repo market. Duffie (1996) defines a special as a repo rate significantly below prevailing market riskless interest rates. This can occur when competition to buy or borrow a particular bond causes buyers in the repo market to accept a lower interest rate in exchange for cash in the transaction. Recently, several empirical analyses have looked into specialness in the repo market, also against the backdrop of quantitative easing policies in major financial markets (Arrata et al., 2020; Jank et al., 2022; Jappelli et al., 2023; Mancini et al., 2016; Roh, 2019). Of particular relevance to our work, Ballensiefen et al. (2023) and Schaffner et al. (2019) document that the euro money market is more segmented when collateral demand is higher. Nguyen et al. (2023) show empirically that a bond's specialness and its responsiveness to monetary policy are related. Pelizzon et al. (2025) show that asset scarcity created by central bank purchases affects arbitrage between European bonds and their futures markets. Our contribution to this literature is (1) to leverage novel data on how collateral demand varies across firms, (2) formalize in a model why such variation matters and (3) structurally estimate a model of collateral demand and document its equilibrium effects on repo markets.

Various papers in this literature evaluate policy interventions of the type we are considering. Greppmair and Jank (2023), Grasso and Poinelli (2025) and Ferrari et al. (2017) find reduced-form evidence that the ECB's reverse repo facility has reduced specialness in repo markets. Klee et al. (2016) reach similar conclusions using US data. Duffie and Krishnamurthy (2016) set out a model in which a reverse repo facility can improve transmission by constraining specialness. Eisenschmidt et al. (2022) set out and estimate a model in which central bank facilities can reduce the market power of intermediaries and improve outcomes including transmission. Our contribution to this specific policy debate comes from our structural model and granular data across multiple assets: this is what allows us to study specialness and, in particular, the effect on outcomes if the Bank of England were to make available on repo markets the *specific* assets that it holds.

The second strand of literature seeks to build and estimate structural models of the repo market. Two particularly relevant papers are Eisenschmidt et al. (2024) and Huber (2023), who build structural models of the European and tri-party US repo market, respectively. Eisenschmidt et al. (2024) seek to understand the impact of market power on the pass-through of monetary policy. Huber (2023) shows that market power has a material impact on spreads earned by dealers when trading with cash lenders. Ioannidou et al. (2022) and Taburet et al. (2024) estimate structural models in other lending markets. We are the first in this structural literature to study and quantify the importance of collateral demand for repo market outcomes.

The third strand focuses on how and why collateral moves through lending markets (Bigio, 2015; Chang, 2019; Chang and Chuan, 2023; Geanakoplos, 2010). Andolfatto et al. (2017), Gottardi et al. (2019) and Infante (2019), for example, focus on rehypothecation in repo markets from a theoretical perspective. Empirical work by Singh (2011) and Aitken and Singh (2010) describe the possibility of collateral rehypothecation as a lubricant to repo market functioning. Our contribution is to show theoretically that collateral demand can have a positive or negative impact on the financing role of repo markets, and to show that empirically this impact is negative.

There is also a literature on the market for lending assets, including for the purposes of shorting (Foley-Fisher et al., 2019, 2016; Sikorskaya, 2023). D'Avolio (2002) and Asquith et al. (2013) look at depository institutions that lend equities or corporate bonds, respectively, and study what that implies for the constraints faced by arbitrageurs. Similarly, Chen et al. (2022) estimate a structural model and demonstrate how market power in the market for equities lending affects asset prices, through the effect on short sellers. We examine asset lending in the context of repo, and quantify how that relates to funding demand.

2 Institutional setting and data

2.1 Institutional setting

In a repo transaction, a firm sells an asset to a counterparty with a commitment to buy it back at an agreed price at a future date. Repo is thus collateralised lending, where the initial seller of the asset is the borrower and the buyer is the lender. The repo rate is the percentage difference between the price at which the lender buys the asset initially and the price at which they sell it back, and can be thought of as the rate of interest on the cash lent. The lender in a repo contract obtains temporary ownership of the asset for the life of the repo contract. They can then use this asset in other transactions by, for example, using it as collateral in another repo transaction or using it to short. This aspect of repo transactions - the fact that the collateral is useful for the lender - and its implications for market functioning are the focus of our paper.

Our setting is the Sterling gilt repo market, where financial institutions write repos with each other backed by UK government bonds (gilts).[5] Participants include banks, hedge

[5]For a broader background on this market, there have been several recent empirical studies on the Sterling gilt repo market. Key topics included the relationship between dealer intermediation and the regulatory framework (Bicu-Lieb et al., 2020; Erten et al., 2022; Kotidis and Van Horen, 2019; Noss and Patel, 2019), the liquidity stress caused by the COVID-19 pandemic (Czech et al., 2021; Hüser et al., 2021), the LDI stress (Pinter, 2023), the impact of central clearing counterparties on repo rates (Benos et al., 2022) and the analysis of repo terms (Julliard et al., 2023).

funds, money market funds, mutual funds, insurers, pension funds, governments and central banks. This market is intermediated by dealers, who borrow from lending institutions and lend to borrowing institutions.[6]

Repo trades can take place over-the-counter or on centralised exchanges. In the UK, almost all trades between dealers and banks are centrally cleared, whilst almost all repos between dealers or banks and non-banks are cleared bilaterally. In contrast to the US market, tri-party repo is rare. See Hüser et al. (2021) for a fuller discussion of the institutional details of repo in the UK.

2.2 The role of funding and collateral demand

Market participants access repo markets for two broad reasons. The first reason is to cheaply and efficiently obtain short-term funding without selling assets, or 'liquidity without liquidation'. Regulation after the Great Financial Crisis incentivised collateralised borrowing rather than uncollateralised borrowing. Repo markets are more stable and more likely to be rolled over than uncollateralised markets, as well as more diversified in that liquidity is supplied by a broad range of firms and not just banks. Repo is arguably the most important source of short-term financing for a broad range of financial firm types.[7]

The second reason is to temporarily obtain or lend out the underlying assets provided as collateral. Firms may want to do this, as opposed to purchasing or selling the underlying asset, for various reasons, including: speculation or hedging through shorting, obtaining

[6] Dealers in gilt markets are typically also banks. In general we will refer to dealers and (other) banks as distinct entities, except in estimating our model where we group them together.

[7] This sub-section is based primarily on a detailed overview of how repo markets are used in practice by the International Capital Markets Association (ICMA). https://www.icmagroup.org/market-practice-and-regulatory-policy/repo-and-collateral-markets/icma-ercc-publications/frequently-asked-questions-on-repo/3-what-is-the-role-of-repo-in-the-financial-markets/.

leverage[8] or for convenience.[9]

2.3 Policy

Our focus is on collateral demand in repo markets. Repo markets are affected by a broad range of policy and regulatory decisions,[10] but we focus on reverse repo facilities as the primary lever through which a central bank can affect collateral demand.

Firms using a central bank reverse repo facility obtain collateral from the central bank and lend it cash. The Federal Reserve has offered a reverse repo facility since 2014, with the explicit objective of maintaining control over short term interest rates.[11] The facility is typically priced at or slightly under the base rate. As of December 2025, for example, the facility is priced at 3.5% (that is, the dealer lending cash and receiving collateral is paid 3.5%) when the current target range for the federal funds rate is 3.5% to 3.75%.[12] The European Central Bank (ECB) introduced such a facility in 2016. The rate is equal to the rate of the deposit facility minus 20bps or the prevailing market repo rate, whichever is lower.[13]

The Bank of England does not directly offer such a lending facility. The UK's Debt Management Office (DMO, part of the Treasury in central government) can temporarily create gilts or obtain them from the Bank of England and lend them to official gilt dealers. It is costlier than the ECB or Federal Reserve equivalents, as it is priced at the base rate

[8] Through, for example, a basis trade (Barth and Kahn, 2021). Alternatively, Liability Driven Investment Funds seek to lever up by borrowing cash against specific assets (Pinter, 2023) (as opposed to a shorting motivation, which involves lending cash against specific assets).

[9] Firms that require a particular bond may find it faster, cheaper or more convenient to temporarily acquire the bond through repo markets. For example, a market-maker in the secondary bond market that receives a buy order for a bond that it does not hold in inventory may choose to temporarily acquire via repo, sell it, and then acquire it at a later date to settle the repo trade.

[10] See https://www.bankofengland.co.uk/markets/bank-of-england-market-operations-guide/our-tools for an overview of the Bank of England's relevant tools.

[11] https://www.federalreserve.gov/monetarypolicy/overnight-reverse-repurchase-agreements.htm.

[12] https://www.federalreserve.gov/newsevents/pressreleases/monetary20251210a1.htm.

[13] https://www.ecb.europa.eu/press/pr/date/2016/html/pr161208_2.en.html.

minus 75bps (as of December 2025)[14] and is infrequently used: total usage of the facility was under £11bn across our whole sample period,[15] relative to average daily repo volumes of over £100bn *per day*. It is intended to prevent specific cases of delivery failure by dealers, rather than to act as a comprehensive securities lending facility such as those offered by the ECB and the Federal Reserve.[16]

We simulate such facilities, along with various design choices, in our counterfactual simulations. We also simulate a swap facility, in which the central bank exchanges one gilt for another in exchange for a fee. To our knowledge, neither the Federal Reserve, the Bank of England nor the ECB directly offer a swap facility of this type.

2.4 Data

The Bank of England Sterling Money Market Data contain detailed transaction data on repo and reverse repo for which the collateral is UK government bonds. Our data include trades reported by banks and dealers between 2017 and 2023.[17] The data include counterparty identifiers, the amount lent, the repo rate, the maturity and the bond provided as collateral. The data also identify where collateral for a trade was "general collateral": in such trades, a clearing house monitors the value of the collateral pledged, and where necessary tops it up by transferring extra collateral from a pre-specified pool of bonds from the cash borrower.[18] In these trades the collateral is therefore not a pre-specified bond, but is an unspecified single bond or combination of bonds from a set of eligible bonds. In some transactions the haircut is also reported.

[14] https://www.dmo.gov.uk/media/rjkd1vs0/repotc070825.pdf.

[15] See https://dmo.gov.uk/data/ExportReport?reportCode=D2.1PROF5.

[16] https://www.dmo.gov.uk/responsibilities/standing-repo/.

[17] Transactions in which neither party is a bank or major broker dealer are omitted in the data, but in practice such transactions are immaterial (Hüser et al., 2021).

[18] General collateral repo transactions against gilts are cleared via the delivery-by-value (DBV) trading mechanism. For further details see https://www.bankofengland.co.uk/-/media/boe/files/news/2013/january/joint-initiative-to-introduce-a-cleared-term-delivery-by-value-service.pdf.

The primary advantage of this dataset relative to others used in the literature is its granular transaction-level detail including complete firm identifiers. This detail allows us to leverage variation across different types of collateral but *within firm*, and then comprehensively track how behaviour in the repo market varies across firms and firm types. We supplement this data with end-of-day prices for government bonds from Bloomberg and granular information from the Bank of England about the government bonds it has on its balance sheet following quantitative easing.

2.5 Repo market features and summary statistics

In Appendix A, we describe various features of the Sterling gilt repo market and report summary statistics. We show that maturities are short, as three-quarters of repo contracts in our sample are either overnight or next day. We document the trading network, which is entirely intermediated (every trade involves at least a dealer or a bank), involves inter-dealer trade (56% of trade is between dealers and banks), is sparse (fewer than 2% of possible counterparty-pairs ever trade) and is relatively persistent through time, particularly on a volume-weighted basis. We describe trading patterns by firm type: money market funds (MMFs) lend, hedge funds lend and borrow in roughly equal proportions, and dealers and banks intermediate but are, on average, net borrowers. These facts are consistent with existing empirical evidence from the literature and are intended to guide our modelling approach. See Appendix A for a fuller description.

One of the facts we show in Appendix A relates to the transmission of monetary policy to repo markets. We measure this transmission as the change in the interdealer repo rate as a percentage of the change in the base rate: if this is not 100%, then transmission is imperfect. We plot the distribution of this measure across monetary policy events in Figure A3 and show that there was substantial noise in transmission over our sample. This is consistent with findings in other jurisdictions (Ballensiefen et al., 2023; Nguyen et al., 2023).

3 Empirical facts

The strength of our data are in their granular detail across firms (including a full set of firm identifiers) and assets. We make use of this to study cross-sectional heterogeneity in repo rates, with a view to understanding how different firms value collateral and funding. In the first set of facts, we examine heterogeneity in collateral demand across firms. In the second set, we unpack this heterogeneity further by looking at the joint distribution of collateral and funding demand. We then discuss what these facts mean for our research question.

Fact 1: Cross-sectional heterogeneity in collateral demand

The presence of collateral demand in repo markets in general is well-established, given that rates differ between special and general collateral (Duffie, 1996). In this section, we consider heterogeneity in collateral demand across firms, given that, in principle, and as described in Appendix A, different firms may use repo markets in very different ways.

First, we study variation in the rates that different firms obtain when lending across different assets. Firms with no collateral demand have the same willingness-to-pay for different assets. Firms with collateral demand for specific assets, on the other hand, will have different willingness-to-pay and so exhibit heterogeneity in rates across assets. For each lender on each date, we calculate the standard deviation in repo rates on their lending, before averaging across time to produce a firm-specific measure. In Figure 1, we plot the distribution of these standard deviations for our whole sample and for 2022 only. We find significant variation across firms: across our whole sample some firms appear to have material collateral demand, whereas many do not. In 2022, there was a period of monetary tightening and gilt market instability (Pinter, 2023), which we show led to a general increase in this dispersion across assets, while material heterogeneity across firms remained.

Second, we consider the extent to which this firm variation corresponds to firm sector.

In the first column of Table 1, we show the standard deviation of a given sector's lending rates on a given day, averaged over our sample period. In the second column, we show the standard deviation for a given day, borrower, and repo maturity bucket. In the third column, we show the standard deviation for a given day, borrower, maturity and lender. In each of these three cases, we retain variation in firms' lending rates across assets.

These results show that some of the variation across firms is explained by their sector. We focus on two sectors: MMFs and hedge funds. There is relatively little variation in the rates at which MMFs lend on a given date, particularly after controlling for other contractual features, whilst hedge funds exhibit large variation. This is consistent with their respective business models. MMFs are the main suppliers of cash in the market and receive the collateral as insurance in the event of default, but typically do not use the collateral to short-sell or to meet obligations from derivative positions. Which collateral they receive is thus not a large driver of their lending rates. Hedge funds, on the other hand, both borrow and lend, and frequently short-sell and trade derivatives (Barth and Kahn, 2021), leading them to require specific assets.

Third, having examined differences in the drivers of repo rates, we also look at differences in the levels of repo rates. Table 2 contrasts the repo rates that firms pay when borrowing from hedge funds and MMFs. Hedge funds typically lend at a lower rate than MMFs. This is true for various fixed effects, including those at the borrower-time level: in other words, the same borrower in the same week pays more to borrow from an MMF than from a hedge fund. The fact that hedge funds in fact earn a worse rate suggests that they gain some benefit from temporary ownership of the collateral that the MMFs do not.[19]

[19]We do not report the same results for dealers, as they earn spreads relative to other types of firm.

Fact 2: The joint distribution of collateral and funding demand

Having established that there is variation in collateral demand, we unpack this further by examining its relationship with funding demand. We do this by looking at trading patterns across general and specific collateral.

First, in Table 3 we report whether firms are net borrowers or net lenders against general and specific collateral. We show that over 25% of firms are simultaneously net *borrowers* against general collateral, but net *lenders* against specific collateral. That is, many firms borrow cash against general collateral, but still use repo markets to obtain specific collateral.

Second, we look at this subset of firms, and show that they lend cash against specific collateral even when the rate they earn is significantly less than the rate they pay when borrowing against general collateral. We show the distribution of this spread in rates in Figure 2. This shows that there are firms that borrow cash against general collateral, but are willing to pay a lot (or more precisely, lend cash at a very low rate) in return for specific collateral.[20]

Third, we compare this spread to the rate at which firms trade general collateral. In Figure 3, we scatter (1) the rate at which a firm on a given day borrows or lends for general collateral, against (2) the spread over general collateral at which it borrows or lends for specific collateral, representing firm-specific specialness. There is a clear positive correlation: firms that transact at higher rates for general collateral (suggesting a greater need for cash relative to other firms) also transact at a greater spread for specific collateral (suggesting they also have a greater need for some collateral). This positive correlation also holds in sub-samples consisting of dealers only or non-dealers only. This cannot be explained by market power differences across firms, as firm-specific specialness is a spread of two rates.

[20]This distribution also shows that in some cases special rates are higher than general rates, implying negative specialness. This is because, as described in Section 2, some pension funds and liability driven investment funds lever up by *borrowing* cash and sending out specific collateral.

Discussion of facts

In fact 1, we document striking variation across firms in how they value collateral, which suggests that firms use repo markets in very different ways, as set out in Section 2. In fact 2, we show that it is not the case that the repo market simply matches firms that want cash with firms that want collateral. Instead, the distribution of preferences across firms is more complicated, with some firms that appear to value cash *and* different types of collateral, both in terms of the direction in which they trade and the rates at which they trade. These facts lead us to build a model to understand how such heterogeneity in preferences can drive equilibrium outcomes.

There are naturally limits to the interpretation of these facts. There could be confounders across firm types, such as relative market power, plus this analysis does not fully account for the fact that these are equilibrium rates that reflect the preferences of counterparties as well as the lending firm's own preferences. These facts also make relatively limited use of variation in trading quantities, which could also be informative about preferences. Building and estimating a model helps us overcome these challenges and obtain clean measures of preferences, which we then interrogate more formally post-estimation.

4 Model

4.1 Overview

Firms trade multiple repo assets on a network. In a repo transaction the borrower temporarily obtains cash in exchange for the bond, whereas the lender obtains the bond in exchange for cash. The transaction specifies the loan amount and the interest rate paid by the borrower to the lender. The assets are heterogeneous only in the bond used as collateral (we abstract away from maturity of the repo, for example).

Firms may have a desire for cash (representing liquidity needs) and a desire for specific bonds as collateral (representing their collateral demand, including for shorting or convenient delivery). The payoffs to cash or collateral are risky, but there is no default risk when transacting. Firms are heterogeneous in their liquidity needs, their collateral demand, their network position (the set of firms with whom they can trade) and their market power. We do not include any central bank facilities in our baseline model as their usage in the data is negligible (as described in Section 2.3), but introduce them in counterfactual simulations below.

4.2 Setup

Assets: Let $\mathcal{A}$ denote the set of distinct assets, which we index by $a \in (0, 1, ..., N_a)$. Assets 1 to N_a each represent repo using a given bond as collateral. Asset 0 represents repo with general collateral that, as described in Section 2 above, does not specify a particular bond. We treat this asset 0 differently in estimation, but within the model it is an asset with its own characteristics like any of the others.

Agents: Firms are heterogeneous in their demands for cash and collateral, in a way we will formalize below. As well as this heterogeneity, there are also two types of firm - dealers and customers - that trade in different ways. Throughout we use indices d and c to refer to dealers and customers specifically, respectively, and i or j to refer to generic firms of either type. There are N_d dealers and N_c customers.

Trading network: We define an adjacency matrix $\mathbf{G}^a$ of size $N_d \times N_c$ that takes the values 0 or 1. If element $G^a(d, c) = 1$ then dealer d and customer c can trade asset a, if $G^a(d, c) = 0$ then they cannot trade. Customers cannot trade directly with each other. This network of trading relationships is exogenous, as in Eisfeldt et al. (2023). All dealers also have access to an interdealer market, which we index by D, and to which customers do not have access. Let $\mathcal{N}_i^a$ denote the set of counterparties to which firm i has access for asset a, including, if firm i is a dealer, the interdealer market.

Dealer to customer trade: Let q_{dct}^a be the net dollar amount borrowed by dealer d from customer c with asset a as collateral on date t. The model is static, and so in the remainder of the model section we omit the t subscript for clarity. q_{dc}^a can be negative, indicating that d lends cash to c and receives the collateral. In some cases in what follows it is convenient to describe the trade from the other perspective, as the net dollar amount borrowed by customer c from d, which we denote q_{cd}^a, where $q_{dc}^a = -q_{cd}^a$. The borrower pays an interest rate of r_{dc}^a. There are no transaction costs, so the interest rate paid by the borrower is the same as the interest rate received by the lender, as in Eisfeldt et al. (2023). We assume that a repo transaction in which \$10m is lent involves the same value of the bond being provided as collateral.[21]

Inter-dealer trade: Dealers do not trade directly with each other, but with an inter-dealer market. Let q_{dD}^a be the net amount borrowed by dealer d from the inter-dealer market D. As for dealer to customer trade, this amount can be negative, the borrower pays an interest rate that we denote by r_{dD}^a and there are no haircuts or transaction costs.

Price-taking behaviour: We assume that dealers have market power with respect to customers, whereas customers are price takers, in keeping with our empirical evidence[22] and existing findings in the literature (Eisenschmidt et al., 2024; Huber, 2023). The extent of the market power faced by a given customer depends on the network structure, and in particular the number of dealers to which it is connected. Conversely, we assume that the inter-dealer market is frictionless and that all dealers take the inter-dealer rate as given.[23] Duffie et al. (2005) and Eisenschmidt et al. (2024) share a similar setup with frictionless inter-dealer

[21]This is the same as haircuts being 0, which is true for over 80% of the transactions in our sample.

[22]We document in Appendix A that dealers earn spreads.

[23]There are 132 dealers and banks in the interdealer market in our data, so each firm would in any case have a small impact on the interdealer rate even if they did internalize their price impact.

trade and frictional dealer to customer trade. Zigrand (2006) makes similar assumptions about some financial agents being price takers and some not, which they call Nash-Walras or Nash-Cournot.

Payoffs from cash and collateral: Let $Q_i^a = \sum_{j \in \mathcal{N}_i^a} q_{ij}^a$ be the total net amount borrowed by firm i against asset a. The firm uses the collateral a that it obtains to undertake a risky project that obtains payoff per unit $\alpha_i^a \sim N(\eta_i^a, \sigma^2)$, where η_i^a represents collateral demand that can vary across assets and firms.[24] Let $Q_i = \sum_a Q_i^a$ denote firm i's total net cash borrowed across all assets. The firm uses this cash to undertake a risky project with payoff $\alpha_i \sim N(\nu_i, 1)$. All draws are independent of each other. Firms are thus heterogeneous in the returns to cash and to temporary ownership of the asset, as captured by ν_i and η_i^a. We do not impose any assumptions about the distribution of these parameters across firms, assets or time (they could, for example, be correlated across firms). Heterogeneity in collateral demand could come from any of the possible motives described above in Section 2.4, including differences in beliefs about the returns to the underlying assets (speculation, in other words) and differences in endowments/pre-existing exposures to those assets (hedging).

Structural errors: Firms may also earn a separate payoff from the transaction that is not directly related to the rate or quantity, which we denote by ϵ_{ij}^a. We call this a structural error as this is what it will represent in estimation. This could represent the importance of specific trading relationships or any other unmodelled shocks to individual transactions. We make no assumption about its distribution here, but consider it in estimation below. Both sides of the transaction obtain their own structural error, and dealers also obtain one from trading with the inter-dealer market.

Other preferences: Firms have mean-variance preferences, with risk aversion $\kappa/2$. The payoffs to a given firm from cash and collateral are normally distributed, such that this is

[24] It would be straightforward to allow σ to vary across firms, time or assets. We consider such robustness checks in our empirical section below.

equivalent to firms having CARA preferences. Firm i's utility is as follows:

$$U_i \equiv \mathbb{E}[W_i] - \frac{\kappa}{2}\mathbb{V}[W_i], \tag{1}$$

where

$$W_i = Q_i \alpha_i - \sum_a Q_i^a \alpha_i^a - \sum_a \sum_{j \in \mathcal{N}_i^a} q_{ij}^a (r_{ij}^a + \epsilon_{ij}^a). \tag{2}$$

Given these preferences and the model of trade described above, the utility to firm i is:

$$U_i \equiv \nu_i Q_i - \frac{\kappa}{2} Q_i^2 - \sum_a \eta_i^a Q_i^a - \sum_a \frac{\kappa}{2}\sigma^2 (Q_i^a)^2 - \sum_a \sum_{j \in \mathcal{N}_i^a} q_{ij}^a (r_{ij}^a + \epsilon_{ij}^a). \tag{3}$$

Firms thus face a quadratic payoff function, with heterogeneity coming from their preferences over cash ν_i and collateral η_i^a, their network position $\mathcal{N}_i^a$, and their type (which determines whether they possess market power). The first four terms show the payoff that the firm gets from the stocks of cash and collateral that result from trading, and the final part shows the payoff from the terms of trade, including any rents from intermediation. We refer to κ and σ collectively as the curvature parameters.

4.3 Equilibrium

We first consider trades between dealers and customers, before considering inter-dealer trade. The first order condition for customer c in the periphery with respect to q_{dc}^a is as follows, remembering that q_{dc}^a is the amount lent from c to d:

$$\underbrace{-\nu_c + \kappa Q_c}_{\text{- } c\text{'s MB from cash}} + \underbrace{\eta_c^a + \kappa \sigma^2 Q_c^a}_{c\text{'s MB from collateral}} + r_{cd}^a + \epsilon_{cd}^a = 0. \tag{4}$$

The customer exchanges cash for collateral, as well as obtaining the repo rate and the structural error. The first order condition for dealer d transacting with customer c with respect to q^a_{dc} has two additional term representing the price effect. The dealer knows the customer's demand curve (Equation 4) and, given that q_{dc} is part of Q_c, strategically adjusts quantity in the standard way: borrowing marginally less from c decreases c's marginal value for cash and increases its marginal value for collateral, both of which decrease the rate at which c is willing to lend to d:

$$\underbrace{\nu_d - \kappa Q_d}_{d\text{'s MB from cash}} - \underbrace{-\eta^a_d - \kappa\sigma^2 Q^a_d}_{d\text{'s MB from collateral}} \underbrace{-\kappa \sum_{l \in \mathcal{A}} q^l_{dc} - \kappa\sigma^2 q^a_{dc}}_{\text{Price effect}} - \epsilon^a_{dc} - r^a_{dc} = 0. \tag{5}$$

These two first order conditions together pin down the equilibrium interest rate and trade, conditional on each firm's other trades.

Turning to interdealer trade, given that it is centralized and frictionless the law of one price means that it must have a single interdealer rate r^a_D per asset. Dealers take this rate as given, and the first order condition for dealer d with respect to q^a_{dD} is as follows:

$$\underbrace{\nu_d - \kappa Q_d}_{d\text{'s MB from cash}} - \underbrace{-\eta^a_d - \kappa\sigma^2 Q^a_d}_{d\text{'s MB from collateral}} - \epsilon^a_{dD} - r^a_D = 0. \tag{6}$$

Finally, to close the model, the interdealer market must clear in each asset (where the dealer to customer part of the market clears by construction as $q^a_{dc} = -q^a_{cd}$):

$$\sum_d q^a_{dD} = 0. \tag{7}$$

We define an equilibrium as repo rates $\{r^a_{dc}\}_{(d,c,a)}$, $\{r^a_D\}_a$ and trading quantities $\{q^a_{dc}\}_{(d,c,a)}$, $\{q^a_{dD}\}_{(a,d)}$ in which (i) agents optimize, taking the rates they pay as given if they are customers

(Equation 4) or dealers trading on the interbank market (Equation 6) and taking into effect their impact on rates if they are dealers trading with customers (Equation 5) and (ii) markets clear for each asset (Equation 7). This system of equilibrium conditions is linear, so we solve for the equilibrium by simply inverting this system of equations. For completeness, we solve for the equilibrium in matrix form and prove its existence and uniqueness in Internet Appendix O1.

We built this model with three objectives in mind. First, we seek to allow for as much heterogeneity across firms and assets as possible. The novelty of our data is in their granular detail across firms and across assets, plus our empirical facts suggest that this variation is large. Second, the model is intended to be structurally estimated. The model gives us tractable, linear estimating equations that allow us to empirically recover the joint distribution of funding and collateral demand as flexibly as possible, while controlling for other drivers of trade including market power and network position. Third, we seek to respect the important institutional features described in Section 2, including, for example, those regarding the network structure.

4.4 Simplified example

To illustrate some of the mechanisms in the model, consider the case with a single dealer (indexed by d), a single hedge fund (c) and a single asset. Let $\Delta\nu \equiv \nu_d - \nu_c$ denote the relative difference in funding needs between them and $\Delta\eta \equiv \eta_d - \eta_c$ the relative difference in collateral demand. For ease of exposition, suppose ϵ_{dc} and ϵ_{cd} are both equal to 0.

Equilibrium net borrowing by d from c follows immediately from the linear first order conditions:

$$q_{dc} = \frac{\Delta\nu - \Delta\eta}{3\kappa(1+\sigma^2)} \tag{8}$$

We make two points with this simple example. First, changes in collateral demand that are *common* to both traders do not affect the quantity traded: Equation 8 makes clear that all that matters is the difference in collateral demand across firms, such that common collateral demand drops out. If, for example, temporary ownership of the asset becomes more valuable to everyone, then this does not affect trade in repo because the increased desire of the lender to acquire the asset is offset by the decreased desire of the borrower to give it up.

The second point concerns the effect of collateral demand on trade volume. One way to think about this would be by reference to the case in which collateral demand is removed by setting $\eta_d = \eta_c = \Delta\eta = 0$. The effect of collateral demand on net borrowing by d from c is obvious from Equation 8: removing collateral demand decreases net borrowing by d if c had relatively greater collateral demand than d.

One minor complication is the fact that net borrowing by d and trade volume are not the same thing: net borrowing can be positive or negative, whereas trade volume is *absolute* net borrowing by d, $abs(q_{dc})$. To illustrate the effect of collateral demand on volume, suppose that $\Delta\eta$ is positive, indicating d has greater demand for the asset. Consider two cases:

- Suppose $\Delta\nu$ is positive and q_{dc} is positive, indicating d is the borrower. In this case, trading volume would be *greater* absent collateral demand, as d's collateral demand decreases its desire to borrow.

- Suppose instead that $\Delta\nu$ and q_{dc} are negative, indicating d is the lender. In this case, trading volume would be *lower* absent collateral demand, as d's collateral demand increases its desire to lend.

In the first case, funding need and collateral demand are positively correlated, and collateral demand reduces volumes. In the second case, funding need and collateral demand are negatively correlated, and collateral demand increases volumes.

To show this more formally, suppose $\eta_k = \rho_{\eta\nu}\nu_k\bar{\eta}$ for $k \in \{d, c\}$, where $\rho_{\eta\nu}$ represents the correlation between a firm's funding needs and its collateral demand, $\bar{\eta}$ represents the level of collateral demand ($\bar{\eta} = 0$, for example, removes collateral demand entirely), and we have omitted any common intercept as it does not matter for trade. The equilibrium gains to trade (GTT) across the two parties are as follows:

$$GTT = \left[\frac{2\Delta\nu}{9\kappa(1+\sigma^2)}\right]^2 (1-\rho_{\eta\nu}\bar{\eta})^2 \tag{9}$$

Suppose that $\rho_{\eta\nu}\bar{\eta} < 1$, implying that collateral demand is not more sensitive to funding need than funding need itself. It follows immediately that gains to trade are increasing in the level of collateral demand $\bar{\eta}$ if $\rho_{\eta\nu} < 0$ and are decreasing if $\rho_{\eta\nu} > 0$.

The intuition for this is that collateral demand affects both demand and supply in repo markets. The presence of collateral demand shifts the demand curve of the borrower *inwards*, as the borrower has to give up collateral that it values. It shifts the supply curve of the lender *outwards*, as the lender obtains collateral that it values. This reduces rates, but the net effect on quantity and gains to trade depends on the relative magnitudes of the shifts in demand and supply. If the shift in demand is larger (which would imply collateral demand is positively correlated with funding demand, as the borrower has higher funding demand than the lender), then quantities and gains to trade go down, and vice versa.

The implication is that the effect of collateral demand on trade depends on its joint distribution with funding needs. If firms with low funding needs have high collateral demand, then collateral demand lubricates the repo market: natural lenders have more reason to lend, implying that collateral demand increases the gains to trade. If, however, firms with high funding needs have high collateral demand, then collateral demand reduces trade in repo: natural borrowers have less reason to borrow.

In the section on counterfactual analysis below, we will undertake exactly this analysis for estimated collateral demand and funding needs across all traders, and show the effect of removing collateral demand on trade and payoffs.

5 Estimation

We now turn to estimating our model. We estimate our baseline model, as opposed to the extension with central bank facilities that we describe below, because we observe extremely little use of the DMO's reverse repo facility, as described in Section 2. The empirical facts described in Section 3 suggest that collateral demand varies across firms and across time, and in the model we show how the effect of collateral demand on repo market functioning depends critically on its distribution across firms and time. Our task in estimation, therefore, is to infer firms' funding needs ν_{it} and collateral demand η_{it}^{a} with as much generality as possible, together with firms' risk aversion κ and the risk associated with collateral demand σ^2.

We aggregate our transactions data to the pair-asset-day level, such that for each pair of firms that write repos on a given day against a given bond, we compute their net repo borrowing against that bond on that day q_{ijt}^{a}, together with the average interest rate on these transactions r_{ijt}^{a}.[25] This gives us a dataset that varies across pairs $i-j$, bonds a and days t. The dealers in our model consist of dealers and banks in our data (because both types have access to the interdealer market), whilst all other types of firm are taken to be customers. In each period we identify the set of firm-counterparty-assets for which trade took place, and use that as the network of feasible trade links.

We estimate a separate funding need ν_{it} for each firm i on day t, and a separate collateral demand η_{it}^{a} by firm i for asset a at time t. As a result, we need to find the unknown parameter vector $\boldsymbol{\Theta} = (\boldsymbol{\nu}, \boldsymbol{\eta}, \kappa, \sigma^2)$: respectively, the vector of firm funding needs across

[25] It was useful in the model to consider dealers d and customers c separately, but in estimation it is more convenient to express things by generic firm i and j.

firms and days, the vector of collateral demand across firms, days and assets, risk aversion and the risk associated with collateral demand. We stack the first order conditions implied by our model for customers (Equation 4) and dealers (Equation 5) to obtain the following estimating equation:

$$r^a_{ijt} = \delta^a_{it} - \left[\kappa \sum_l q^l_{ijt} + \kappa\sigma^2 q^a_{ijt}\right] \mathbb{1}_{ij} + \underbrace{\delta_{ij} + u^a_{ijt}}_{\epsilon^a_{ijt}} \tag{10}$$

where $\mathbb{1}_{ij}$ is an indicator variable that takes the value 1 if i is a dealer in the core and j is in the periphery (indicating market power), and 0 otherwise, and where we have disaggregated the pairwise shock ϵ^a_{ijt} into an $i-j$ fixed effect and a residual u^a_{ijt}.[26] Assuming that the pairwise structural shock is mean zero within each $i-t-a$ bucket,[27] the fixed effect δ^a_{it} can then be disaggregated further as follows:

$$\delta^a_{it} = \nu_{it} - \kappa Q_{it} - \eta^a_{it} - \kappa\sigma^2 \sum_m q^a_{imt} \tag{11}$$

Our estimating approach involves two steps: first to estimate the curvature parameters[28] κ and σ^2 and the fixed effects δ^a_{it} from estimating Equation 10, and second to decompose the estimated fixed effects into ν_{it} and η^a_{it} using Equation 11. Estimating a fixed effect in a first step and then decomposing that fixed effect into its drivers in a second step is not uncommon in the empirical industrial organization literature (see, for example, Nevo (2000)).

[26]The pairwise fixed effect helps insulate our curvature estimates from unobserved pair-specific variation. This could, for example, be in the extent to which each pair centrally clears the transaction, which might have implications for rates.

[27]This assumption implies that the structural error might lead a given firm to trade more with one counterparty than another. The firm does not, however, have unmodelled reasons to borrow or lend specific assets beyond its collateral and funding demand.

[28]In our model we normalize the risk of the project undertaken with cash to 1. This normalization has no impact on the model or the estimation (as all that matters is overall curvature in the model, which we can specify and estimate with only κ and σ), but it does mean that our estimate of κ should be interpreted as a generic curvature parameter rather than specifically risk aversion.

We discuss each step in turn.

Step 1: Estimating curvature parameters

Dealers earn a spread when trading with customers, as described in Appendix A. The market power in our model implies that the size of this spread and its variation with quantities is informative about the curvature parameters, as in estimating Equation 10. The primary challenge is that rates and quantities are jointly determined, so we need exogenous variation in trading quantity q^a_{ijt}.

We obtain this variation by making use of the facts that (a) firms differ in the bonds against which they borrow, (b) the prices of different bonds vary differentially through time, and (c) these prices are plausibly exogenous, in that they are unlikely to be affected by the repo transactions of individual pairs of firms - we emphasise here that we include firm-time-bond fixed effects δ^a_{it} within step 1 of our estimation, so the only remaining variation is within individual pairs of firms within the repo market. As a result, we can use variation in bond prices to isolate exogenous variation in firm j's net demand for cash and collateral in Equation 10, and use this to identify the slope of i's net demand for cash and collateral, which gives us κ and σ.

Formally, we compute two instrumental variables for the two endogenous terms in Equation 10, which capture j's net demand for cash and asset a at time t. To do so, for each firm j at time t we construct a measure of their "wallet": the subset of bonds which they hold, and against which they can borrow. We look at the preceding 4 weeks, and identify the set of bonds ω_{jt} against which firm j borrowed, and the amount of their borrowing that was against each of these bonds s^a_{jt-1}, for all a in ω_{jt}. We then construct the sum of the prices of the bonds in j's wallet, weighted by their amount of borrowing against each asset s^a_{jt-1}:

$$z_{1,jt} = \sum_{a \in \omega_{jt}} s^a_{jt-1} \times \text{price}^a_t \tag{12}$$

If this decreases, this means j has a lower value of collateral against which they borrow, which means their ability to borrow is more constrained. As a result, we should see a positive relationship between j's borrowing and its instrument $z_{1,jt}$.

We then construct a second instrument as follows:

$$z^a_{2,jt} = z_{1,jt} - s^a_{jt-1} \times \text{price}^a_t \tag{13}$$

This is the change in the value of the bonds in j's wallet, *except asset a*. If this decreases then the other assets in j's wallet are less valuable, which means that – conditional on the value of a not changing – they will aim to borrow more heavily against bond a to fill the shortfall. As a result, we should see a negative relationship between j's borrowing in a and its instrument $z^a_{2,jt}$.

We use these instruments in the following first-stage regressions for the two endogenous variables in our estimating Equation 10:

$$\begin{aligned} q^a_{ijt} &= \alpha^a_{1,it} + \beta_1 z_{1,jt} + \beta_2 z^a_{2,jt} + \alpha_{1,ij} + e^a_{ijt} \\ \sum_l q^l_{ijt} &= \alpha^a_{2,it} + \beta_3 z_{1,jt} + \beta_4 z^a_{2,jt} + \alpha_{2,ij} + e^a_{ijt} \end{aligned}$$

These instruments are in effect shift-share instruments, where the shares are determined by the amount of borrowing of firm j against different bonds. The instruments shift j's net demand and thus identify the slope of i's net demand. The identifying assumption is that these instruments are independent of the pairwise shocks u^a_{ijt}, which in turn requires that bond prices and the shares used in computing our instrument are independent of these shocks.

The independence of pairwise shocks and bond prices is – given the demanding fixed effects we include – a relatively mild assumption. It is highly likely that developments in repo markets impact bond markets: if, for example, the hedge fund sector wishes to borrow a bond for shorting reasons, one would expect its price to go up. However, our regressions include firm-bond-date fixed effects, so this variation is stripped out. The pairwise shocks to repo u_{ijt}^a are unlikely to be of sufficient magnitude to impact prices in bond markets. We lag the firm's wallet so as to remove any contemporaneous correlation between firm trading and the unobserved shocks. If these unobserved shocks are not serially correlated, then our instrumental variable is valid.

Step 2: Estimating funding and collateral demand

In the first step, we estimate δ_{it}^a and we recover estimates of κ and σ. In the second step of our estimation, we use these estimates to recover funding and collateral demand. Given Equation 11 and the estimates from the first step, the only remaining unknowns are η_{it}^a and ν_{it}, as everything on the left-hand side of the following equation is known:

$$\delta_{it}^a + \kappa Q_{it} + \kappa\sigma^2 \sum_m q_{imt}^a = \nu_{it} - \eta_{it}^a \tag{14}$$

Variation across assets clearly pins down variation across η_{it}^a, as ν_{it} does not vary across assets. The only remaining complication is to separately identify the level of ν_{it} and the average level of η_{it}^a. To do so, we make use of the general collateral asset: as described in Section 2.1, when trading this asset the lender does not require a particular bond in return. We therefore assume that the collateral demand for this particular asset is equal to 0. This is a normalization of preferences that does not imply, for example, that the choice between specific and general collateral is exogenous. We have chosen it to imitate how specialness is defined in repo markets, as the spread between the general and specific collateral rates (Duffie, 1996). Our estimates of collateral demand should thus be interpreted as the specialness of specific collateral relative to general collateral, excluding any specialness or desirability that is common to all gilts including general collateral.

This assumption allows us to pin down ν_{it} and η_{it}^a by re-arranging Equation 14 as follows (noting again that all variables and coefficients on the right-hand side are known as they are either data (q terms) or have been estimated in the first step (κ, σ and the δ terms)):

$$\begin{aligned}\nu_{it} &= \delta_{it}^0 + \kappa Q_{it} + \kappa\sigma^2 \sum_m q_{imt}^0 \\ \eta_{it}^a &= \delta_{it}^0 - \delta_{it}^a + \kappa\sigma^2 \sum_m (q_{imt}^0 - q_{imt}^a)\end{aligned} \tag{15}$$

where a superscript of 0 denotes general collateral.

This approach allows us to semi-parametrically recover the joint distribution of collateral demand across assets, firms and time from variation in rates and quantities (semi-parametric in the sense that we impose that $\eta_{it}^0 = 0$ for general collateral, but otherwise make no assumptions about the shape of that distribution across firms, times or assets that are not general collateral).

Identification comes from the joint distribution of rates and quantities. In general terms, we conclude that a firm has high funding demand if it trades general collateral repo at a high rate, if it borrows a lot, and if it borrows a lot against general collateral repo. A firm has high collateral demand for a given asset if it trades that asset at a discount relative to general collateral, and if it lends a lot against that asset relative to its lending against general collateral. We emphasize also the relationship between this structural identification and empirical fact 2 in Section 3: both are built around identifying firms that obtain and are willing to pay for both cash and specific collateral. We set out a cross-check providing further detail on the nature of our identifying variation in Appendix B.

The data do not indicate whether in a particular trade the dealer is satisfying its own needs for cash or collateral or whether it is intermediating. Using the joint distribution helps us partially separate these two motives, and so recover the dealer's preferences over cash and collateral. In particular, Q_{it} is *net* borrowing across counterparties. A dealer that purely intermediates would lend as much as it borrows and its Q_{it} would be 0, whereas a dealer that borrows more than it lends would have positive Q_{it}. All else being equal, we would conclude that the former has lower funding demand than the latter.

We discuss in the following section and in Appendix B the various cross-checks of our estimation and robustness tests that we run.

6 Results

We first describe the results of our estimation. We then show how our estimated collateral and funding demand vary in the time series and the cross-section, with implications for repo market functioning. We then discuss various cross-checks and tests for robustness.

6.1 Parameter estimates

Table 4 shows the results of the first part of our estimation approach, which is to estimate Equation 10. We show results from an OLS regression in the first column, and from our two-stage least squares approach in the second. The signs are as expected, and the coefficients are highly statistically significant. The first coefficient provides an estimate of minus the curvature parameter κ, whilst the second estimates $-\kappa \times \sigma^2$, where σ^2 is the variance of the return firms earn using the assets they demand as collateral.

Table 5 shows the results of regressing the endogenous regressors in our estimating equation on our two instruments, equivalent to the first stage of our two-stage least squares approach. The first stages are strong, with the the instruments showing high predictive power for the endogenous regressors. The signs are broadly intuitive: an increase in the value of j's collateral ($z_{1,jt}$) is associated with an increase in its net borrowing from i (or equivalently, a decrease in i's net borrowing from j). An increase in the value of j's collateral *except* asset a leads it to decrease its net borrowing from i (equivalent to increasing i's net borrowing from j) against a, as it needs to rely less on asset a in its borrowing.

The results of the two-stage least squares approach imply values of 0.02 for curvature parameter κ and 9 for the risk on the return to obtaining collateral σ^2. In other words, the model implies that the risk associated with collateral demand is materially larger than that associated with funding (which we normalized to 1 in the model).

6.2 Collateral demand and funding demand

The key outputs of our estimation are estimates of funding demand ν_{it} and collateral demand η^a_{it}, which we estimate semi-parametrically as described in Section 5. In this section we document how funding and collateral demand vary in the time series, across firms and across assets.

6.2.1 Macro drivers

Our model showed that the joint distribution of funding and collateral demand determines repo market outcomes. What shapes this distribution? Here we establish how changes in the macroeconomy and financial markets drive time series variation in these variables.

Figure 4 shows how funding and collateral demand vary through time. We plot the 10^{th}, 50^{th} and 90^{th} percentiles of funding demand ν_{it} in the left panel and of collateral demand η^a_{it} in the right panel. Funding demand closely tracks the central bank's policy rate over this same period. This is intuitive: the net demand for funding via repo contracts should depend on the cost of alternative funding. As policy rates change, this is passed through into other funding markets. As a result, the monetary policy tightening from 2022 onwards led to an increase in the marginal cost of funding in the repo market.

Our estimated collateral demand follows a different trajectory to funding demand. It rises in March and April 2020 (the grey highlighted region) and from the end of 2021, reaching a peak in October 2022. These two periods coincide with two key moments of market turmoil in UK financial markets: the dash-for-cash in March 2020 (Czech et al., 2021; Hüser et al., 2021) and the gilt market turmoil in the autumn of 2022 (Pinter, 2023). We explore this further in Figure 5. Prior literature argues that short selling should be more prevalent in periods of greater disagreement (D'Avolio, 2002; Sikorskaya, 2023). In Figure 5 we plot daily implied interest rate volatility against the mean and the dispersion of our estimated collateral demand. Implied interest rate volatility explains a large amount of time series variation in collateral demand. This is in line with the findings for stocks in Sikorskaya (2023).

This suggests that short selling is quantitatively a key driver of repo market outcomes. In stable periods with little disagreement, there is little incentive to engage in short selling. In this case, collateral demand is low and the repo market operates as a standard secured funding market. By contrast, when volatility increases so does the desire of market participants to short sell assets, and to use the repo market to do so. In this case the repo market serves two functions simultaneously: facilitating funding and the obtaining of collateral to short sell assets. Collateral demand is thus greater in times of uncertainty, when funding needs may be most acute.

6.2.2 Variation across firms

One contribution of our estimation is to produce estimates of collateral demand that vary across firms, relative to a literature that generally studies this at the asset level (Schaffner et al., 2019). Our model shows that this variation across firms is a key driver of repo market outcomes. We first show how funding demand and collateral demand vary separately across and within firm types, before examining their co-movement.

Table 6 summarises variation in funding and collateral demand across firm types. In the first column we regress funding demand ν_{it} on dummies for the type of firm i. MMFs have lower funding demand, consistent with their role as lenders in these markets. Dealers, by contrast, have amongst the highest funding demand, consistent with their reliance on repo markets for funding.

In the second column of Table 6 we regress collateral demand η_{it}^{a} on dummies for firm type. Pension funds (PFLDIs) have the lowest collateral demand. This is consistent with their business model in this period: they sought to hold certain long-dated assets to hedge their liabilities, and leverage up by *borrowing* against that particular asset (Pinter, 2023). These firms thus often exhibit negative collateral demand. MMFs and funds also have relatively low collateral demand, consistent with them making limited use of the collateral they obtain by, for example, shorting trades.

Dealers have particular high collateral demand, followed by hedge funds. Hedge funds' high collateral demand is consistent with their trading strategies, for example speculative short-selling strategies. It is perhaps more surprising that dealers have such high collateral demand, as these are less likely to be using repo to speculate in asset markets. Instead, their collateral demand could represent them using repo to hedge exposures rather than speculate and to source assets cheaply for their clients.

Finally, we consider what the variation across firms implies for the correlation between funding demand and collateral demand. In Table 7 we regress collateral demand on funding demand with various fixed effects: the first column shows the unconditional relationship between the two, the second shows the correlation within days across firms, the third shows the correlation within firms across time, and the fourth shows the correlation within sector-date fixed effects. In each case the coefficient is positive, indicating that a high demand for cash tends to be accompanied by a high demand for collateral. This is also consistent with our second reduced-form fact in Section 3, which suggests that some firms need both cash and specific collateral.

6.2.3 Collateral demand and asset characteristics

In this section, we study how collateral demand depends on the characteristics of the asset being traded. We study four characteristics of a bond: its age, its residual maturity, the size of its float, and whether it is on-the-run or off-the-run. Ultimately all collateral demand is driven by asset characteristics (given that a bond can be summarised as a collection of characteristics): if a hedge fund seeks to short a particular part of the yield curve, for example, then it has collateral demand for bonds with the corresponding maturity. In this section, we consider whether there are particular characteristics that are consistently more demanded.

First, we study maturity, and find that there is a large discontinuous jump in collateral demand as bonds pass from over to under 10 years residual maturity. We show the relationship between a bond's collateral demand and its residual maturity, conditional on controls including date and firm fixed effects, in Figure 6a. As a bond crosses the 10-year residual maturity threshold, collateral demand jumps by 0.1 relative to a mean of 0.12. This discontinuity is, to our knowledge, a novel finding in repo markets, which could be explained by the treatment of maturity by central counterparties and central banks. Dealers and banks often use government bonds as collateral in other transactions, in particular as margin with central counterparties (across securities financing transactions and derivative transactions) and their borrowing from the central bank, where they pre-position collateral with the central bank in case they need to borrow. In both cases, there is a discontinuously lower haircut applied to this bond as collateral when its maturity passes under 10 years.[29,30] This causes the bond's scarcity to increase as it is increasingly held by central counterparties and central banks, who are less likely to make them available for lending, which would lead to increased collateral demand.

Second, we study the age of the bond, and find that collateral demand increases in the period after issuance, before peaking after around 3 years. To show this, we regress collateral demand on age dummies along with controls and date and time fixed effects, and plot the estimated coefficients in Figure 6b. The resulting pattern is consistent with changing scarcity as the underlying bonds trade in the secondary market, and mirrors patterns in other repo markets. As Keane (1996) notes, after issuance bond holdings gradually migrate from dealers to long-term buy and hold investors, who are less likely to lend them out. As a result, the bond is less available for lending in the repo market, and the value traders place on obtaining it increases.

Third, we consider scarcity and whether the bond is on or off the run in Table 8. We regress collateral demand η_{it}^{a} on the log of the float of the bond, which measures the amount in issuance minus the amount held by the central bank, and dummies for whether the bond is the first, second, third, or fourth bond off-the-run, along with controls and date and firm fixed effects. The greater a bond's float, the lower is its collateral demand. This supports the argument in Nguyen et al. (2023) that scarcity drives collateral demand. We find relatively little difference in repo rates between the on-the-run bond and the first off-the-run bond, but thereafter collateral demand shrinks significantly as bonds are supplanted by more recently issued bonds (Duffie, 1996).

[29] https://www.bankofengland.co.uk/-/media/boe/files/markets/eligible-collateral/summary-tables-of-haircuts-for-bank-lending-operations.pdf.

[30] https://www.lseg.com/content/dam/post-trade/en_us/documents/lch/ccp-disclosures/lch-sa-acceptable-haircut-schedule-q4-2023.pdf.

6.2.4 Discussion

We summarize above variation in collateral demand across time, firms and assets. We make the following observations about what our results mean for the counterfactuals that follow.

Through the lens of our model, positive correlation in collateral demand and funding demand suggests that gains to trade would be higher absent collateral demand. One of the drivers of this positive correlation is that dealers, who play a central role in this intermediated market, have relatively high collateral demand and funding demand. The variation over assets suggest that there are some consistent drivers of collateral demand that apply across firms and time. Bonds that are particularly desirable and hard to source on repo markets, whether because of maturity rules, age effects or the size of their float, have high collateral demand. In our counterfactuals we ask what would happen if central banks were to supply such assets. The material variation over time, however, suggests that the effect of collateral demand on outcomes is also likely to be variable. Similarly the usage and impact of central bank facilities that supply assets with high collateral demand is also likely to vary.

6.3 Cross-checks and robustness

We run two cross-checks of our approach and describe the results in Appendix B. First, we illustrate our identifying variation by regressing our estimated parameters on the terms in Equation 15, and showing their incremental explanatory power. This makes clear, for example, the extent to which differences in trading volumes across firms drive identification relative to differences in rates. Second, having established how our model and estimation strategy map empirical variation in transaction terms into estimated variation in model parameters, one might reasonably ask what advantages this structural approach brings relative to simpler reduced-form approaches. We implement various simpler approaches, and show that they imply materially different empirical distributions of collateral and funding demand.

This suggests that there is potentially significant added value to our structural approach.

We also show the key features of our results are robust to alternative specifications regarding (1) whether we estimate our model solely using overnight and next day repo rather than including longer term repo as well, (2) whether collateral demand varies depending on whether it is incoming or outgoing for a given firm, (3) how we weight the bonds in our instrumental variable, (4) allowing curvature parameters κ and σ^2 to vary through time, and (5) omitting the ten most frequently traded bonds from our sample. We set out the results of these exercises in Appendix C.

7 Counterfactuals

7.1 Equilibrium effects of collateral demand

In this section, we seek to understand the equilibrium effects of collateral demand on repo market outcomes. We do this by running counterfactual analyses in which we remove collateral demand entirely: we set η_{it}^a to zero for all firms, assets and time periods. The sole motive for trade in the repo market would then be to obtain funding. Given our estimation procedure, this is equivalent to asking what would happen if all firms valued all specific collateral in the same way that they currently value general collateral.

We set out the results in Table 9. The rows set out various market outcomes and the columns show our baseline and the counterfactual without collateral demand. Our primary finding is that both aggregate trading quantity and realised gains from trade would be materially higher without collateral demand. These findings are at odds with the idea put forward by Singh (2011) that collateral demand can lubricate financing via repo. This result is not due to any friction or inefficiency or the network topology, but is due to the distribution of preferences across firms. Collateral acquisition via repo in a sense crowds out financing via repo, as firms that need funding in relative terms also care more about giving up the underlying collateral.

Our second finding concerns the effect of collateral demand on rates. Unsurprisingly, repo rates would be higher absent collateral demand, as lenders no longer benefit from collateral demand and borrowers no longer need to forego their own collateral demand. We also find that dispersion in rates across assets would be significantly lower absent collateral demand. The remaining variation is due to heterogeneity in funding demand, network structure and market power.

We unpack these results further in Figure 7, which shows the effect of collateral demand over time under various bases. We reach three conclusions on the basis of this figure. First, the impact of collateral demand is time-varying. The blue solid line shows the effect of collateral demand on realised gains from trade through time. As collateral demand peaks towards the end of our sample, so does the impact of collateral demand on trading activity.

Second, we study *whose* collateral demand matters: we find that the effect of collateral demand is driven by dealers and banks. We show this in an alternative counterfactual in which we set the collateral demand of all dealers and banks to 0, but leave the collateral demand of other market participants unchanged from our estimated values. We plot the impact of this on gains from trade as the red dashed line in Figure 7. The effect accounts for almost all of the effect in our first counterfactual. Dealers and banks sit at the heart of the repo market whilst simultaneously intermediating, managing their own funding needs and their own collateral demand in order to hedge risk. Our results speak to the inability of dealers and banks to simultaneously do all of these things using repo.

Third, we confirm that our results are driven by the joint distribution of collateral and funding demand across traders. In Section 4 we show in theory that positive correlation between collateral and funding demand implies that collateral demand depresses repo market activity, and in Section 6 we show that empirically this correlation is indeed positive. To demonstrate that it is indeed this positive correlation that drives our results, we run a second counterfactual. We first rearrange collateral demand across firms to reverse the positive correlation we estimate in Table 7, such that there is instead negative correlation of the same magnitude. We then calculate the resulting equilibrium. The green dashed line in Figure 7 shows the impact of collateral demand in this alternative set-up. The sign of our results reverses: if collateral demand were negatively correlated across firms with funding demand, then its removal would decrease quantities traded and realised gains from trade. This confirms that the joint distribution of collateral demand and funding demand across firms is the key determinant of the impact of collateral demand on repo outcomes.

7.2 Central bank facilities

In this section, we use our estimated model to counterfactually simulate central bank facilities offered to dealers. We consider two types of facility: (1) a reverse repo facility in which the central bank lends bonds and borrows cash, and (2) a swap facility in which the central bank exchanges one bond for another. We then consider a further two design choices: (1) the price of the facility and (2) whether the facility is unconstrained in the number of bonds it can lend, or whether it is constrained to only lending bonds that the central bank has previously bought via quantitative easing.[31] These design choices speak to ongoing policy debates about whether and how to implement these types of facilities.

We extend our model to include these facilities, and solve for the new equilibrium leaving all other parameters (notably funding and collateral demands) unchanged. We leave the network unchanged, meaning that we do not allow firms to form new connections in response to these facilities.[32] We then quantify the impact of these facilities on key market outcomes,

[31] We summarise the variation in central bank purchases across bonds in Table A2.

[32] In this sense, we study the intensive margin, rather than the extensive margin. The topology of the network determines the extent to which individual dealers possess market power over specific customers, and

including equilibrium rates, quantities, monetary policy transmission and the total surplus earned by market participants. We formally derive the equilibrium conditions with these policy facilities in Appendix D, and show in each case that the equilibrium exists and is unique in Online Appendix O1. With a central bank facility the equilibrium is now nonlinear, so we solve for it numerically.

In the remainder of this section, we first give an overview of and provide intuition for the effects of such facilities. We then describe our quantitative results regarding, in turn (1) how trading behaviour changes and (2) what this means for surplus.

7.2.1 Overview and intuition

We briefly illustrate the mechanisms involved using a simple example. For ease of exposition, suppose that there are no customers, and trade consists only of transactions between dealers. Suppose further that $\epsilon^a_{dD} = 0$ for all d, a. We rearrange and average the dealer's first order condition, Equation 6, across dealers to obtain the interdealer rate for asset a:

$$r^a_D = \bar{\nu} - \bar{\eta}^a - \kappa\bar{Q} - \kappa\sigma^2\bar{Q}^a, \tag{16}$$

where $\bar{\nu} = \frac{\sum_d \nu_d}{N}$, and similarly for $\bar{\eta}^a$, $\bar{Q}$ and $\bar{Q}^a$. We now take the mean of both sides over assets, to obtain an expression for the mean interdealer rate:

$$\bar{r}_D = \bar{\nu} - \bar{\eta} - \kappa(1 + \sigma^2)\bar{Q}, \tag{17}$$

where in a slight abuse of notation $\bar{r}_D = \frac{\sum_a r^a_D}{N_a}$, $\bar{Q} = \frac{\sum_a Q^a}{N_a}$, and $\bar{\eta} = \frac{\sum_a \bar{\eta}^a}{N_a}$.

so is important in estimation. It is arguably less important in counterfactuals because of the presence of the frictionless interdealer market. Suppose, for example, that a given dealer trades an asset with a single counterparty. Now suppose that some counterfactual change takes place that prompts the dealer to want to trade much more of that asset. We do not allow the dealer to form additional connections with customers to trade that asset in response, but the dealer can in any case frictionlessly trade that asset with the interdealer market.

Baseline: In our baseline, market clearing requires that $\bar{Q}_a = \bar{Q} = 0$, as there are only dealers in the market in this example. It follows that interdealer rates across assets and average interdealer rates are simply a function of average preferences: $r_D^a = \bar{\nu} - \bar{\eta}^a$ and $\bar{r}_D = \bar{\nu} - \bar{\eta}$. Collateral demand means that $\bar{\eta} > 0$, so mean interdealer rates $\bar{r}_D$ are lower than the base rate.

Reverse repo facility: We model a reverse repo facility in which a dealer can lend cash to the central bank at rate r_{CB}[33] and receive bonds in return. We now define the interdealer market to include dealers' transactions with the facility. The interdealer market need no longer clear with zero net lending, as collectively dealers can obtain bonds from the central bank in return for cash, in which case $\bar{Q} < 0$ and $\bar{Q}^a < 0$. Given Equation 17, it follows that repo rates are weakly greater with the facility.

This can also be seen by analysing a dealer's choice between lending to other dealers and lending to the facility. The rate of an unconstrained facility acts as a floor on repo rates: if equilibrium interdealer repo rates were lower than the facility rate, dealers would be better off simply lending to the central bank instead of each other. By increasing rates for the most in demand assets, this floor also reduces rate dispersion across assets. The scale of the facility usage to support such a rate depends on the curvature parameters κ and σ.

This intuition also sets up the design choices we discuss below. The price of the repo facility sets the floor on the repo rate: the lower the floor, the smaller the effect of the facility. Similarly, a constraint on the amount that the central bank can lend may make the floor non-binding for some assets.

Swap facility: With a swap facility, dealers can obtain assets from the central bank in exchange for others, at a per-unit cost r_{CB}. Dealers will obtain bonds that have high collateral demand and low repo rates (that is, $\bar{Q}^a < 0$ for these assets) in exchange for bonds with low

[33]It would be straightforward to allow this to vary across assets, but we match real world such facilities by setting a single rate for any bond.

collateral demand and high repo rates ($\bar{Q}^a > 0$). The effect of facility usage in Equation 16 thus reduces dispersion in rates. This can also be seen by analysing a dealer's decision between using the facility and trading with other dealers: it cannot be that any two assets differ in equilibrium repo rates by more than the price of the swap facility, otherwise there would be an arbitrage opportunity. The central bank does not inject any cash using a swap facility, so in equilibrium $\bar{Q} = 0$ as in our baseline and the average repo rate is unchanged.

Thus while the reverse repo facility acts as a floor that pushes up rates, the swap facility acts as a collar that compresses rates around the mean. The effect of such a facility depends on its design. A cheaper swap facility makes the collar tighter and further reduces dispersion across assets. As with the reverse repo facility, if the swap facility is constrained in the number of bonds then the collar it places on rate differences need not always bind.

Monetary policy transmission: We discuss above and show in Figure 4 that average funding demand $\bar{\nu}$ moves very closely with the base rate, which is intuitive as the base rate shifts dealer preferences over cash. In this example, we therefore think of monetary policy as changing $\bar{\nu}$.[34] Average collateral demand is positive, so mean interdealer rates $\bar{r}_D$ are lower than the base rate.

Monetary policy seeks to change $\bar{r}_D$ by changing $\bar{\nu}$. As we will show quantitatively below, the transmission of monetary policy to $\bar{r}_D$ is noisy. This is because this equilibrium rate varies with collateral demand $\bar{\eta}$ as well as the base rate, meaning that if collateral demand changes after a policy change, the policy change need not be passed-through one-to-one to repo rates.

A reverse repo facility can improve transmission, by binding average repo rates to the facility rate from below. Usage endogenously responds to changes in collateral demand: if $\bar{\eta}$ goes up sufficiently after a change in the base rate, then $\bar{Q}$ becomes negative as banks obtain

[34] In our full counterfactual we simply simulate equilibrium repo rates holding the base rate, funding and collateral demands constant, without requiring any assumption about exactly how the base rate affects these preferences.

the bond from the facility, which pushes rates up (Equation 17), taking them closer to the policy rate. Suppose, for example, that collateral demand for all assets was weakly positive, and an unconstrained central bank facility was priced at the base rate for all assets. This sets a floor on the repo rate at the base rate, meaning perfect pass-through is assured.

A swap facility does not improve transmission. This can be seen directly from Equation 17: the swap facility does not change $\bar{Q}$, so cannot change average repo rates nor the transmission of monetary policy to average repo rates. Instead, the swap facility narrows rates around this average.

7.2.2 Results: Usage and transmission

We show the quantitative effects of central bank facilities in Table 10 and Figure 8. Each row in Table 10 corresponds to a market outcome, such as the mean repo rate. We split some of these outcomes into before January 2022, when collateral demand was relatively low, and afterwards, when it was high.[35] Each column corresponds to a different type of facility. In the first column, we show our baseline with no facility. In the second and third columns, we show an unconstrained reverse repo facility priced at 35bps and 5bps below the base rate, respectively. In the fourth and fifth columns, we show a reverse repo facility at 35bps and 5bps below the base rate, respectively, that is constrained to only lending out bonds that the central bank had on its balance sheet due to quantitative easing. In the sixth and seventh columns, we show unconstrained and constrained swap facilities, respectively, each priced at 70bps.[36]

The final two rows of Table 10, together with Figure 8, summarize monetary policy transmission. We compute the transmission of a change in the central bank base rate at time

[35]We do not split the results for monetary policy transmission, as there were very few changes in the base rate in the first part of our sample.

[36]The swap facility can be thought of as a reverse repo transaction in one asset combined with a repo transaction in another, so we chose 70bps as similarly priced to the reverse repo facility at a 35bps discount.

t into repo rates at time $t + \tau$ as the change in average interdealer repo rates as a percentage of the change in the base rate. Figure 8 summarizes transmission in the $\tau = 1, ..., 25$ days following a base rate change, in the baseline and with various facilities. In each case, we show the 10^{th}, 50^{th} and 90^{th} of transmission across the 15 policy rate changes in our sample. The penultimate row in Table 10 shows the median transmission across all base rate changes and all τ. Our primary variable of interest[37] is the difference between the 90^{th} and 10^{th} percentiles, which we call *transmission noise* and set out in the final row. When we talk about an improvement in the transmission of monetary policy, we mean a reduction in this noise.

We reach five conclusions based on our simulations:

1. An unconstrained reverse repo facility would be heavily used, would reduce rate segmentation across assets, and would improve the transmission of monetary policy.

2. An unconstrained swap facility would also be heavily used and would reduce segmentation but not improve transmission.

3. Constrained facilities would have material, but much smaller, effects on segmentation and transmission.

4. The effect of such facilities depends on their pricing, with less competitively priced facilities having smaller effects.

5. The effect of such facilities is state-dependent, and would have varied materially between times with low and high collateral demand.

We discuss each in turn.

[37]Note that the median transmission is not particularly important: if the repo rate consistently changes by some factor of the base rate, then the policy maker can take this into account when setting the base rate and thus have perfect control of repo rates.

First, an unconstrained reverse repo facility priced 35bps below the base rate would be heavily used when collateral demand is high, and significantly impact market outcomes. Such a facility constrains the interdealer rate in all assets to be no more than 35bps below the central bank rate, and in doing so pushes the mean interdealer rate from 38bps below the base rate in our baseline to 10 bps below. It reduces segmentation, by reducing the range in interdealer rates across assets. Usage of such a facility would be extremely high: facility usage would have been around 5 times mean baseline volume.

Such a facility would materially improve monetary policy transmission. As the first panel of Figure 8 shows, transmission is imperfect in the baseline: whilst on average repo rates change by the same amount as the base rate, they often undershoot or overshoot by a large amount. As the second panel shows, the facility significantly narrows this variability, with transmission noise falling by 40%. By setting a floor on repo rates, the facility more closely binds repo rate changes to base rate changes.

Second, an unconstrained central bank swap facility would also be heavily used, and would reduce segmentation but not improve transmission. The collar imposed by the facility on rates reduces the standard deviation in repo rates across assets from 20bps in our baseline to 17bps, and so reduces segmentation across firms trading different assets. As Table 10 shows, monetary policy transmission barely changes because, as described above, collateral swap facilities do not change aggregate net lending and so do not change mean repo rates. As in the case of the reverse repo facility, usage would be a large multiple of daily volume.

Third, constrained facilities have material, but smaller effects on outcomes. We summarise the variation in central bank holdings across assets in Table A2. When we constrain the facility to only lend out the assets we know that it holds, the floor or collar that the facility places on interdealer rates is imperfect.[38] Consider a constrained reverse repo facility.

[38] This can be seen from the fact that the lowest repo rate with the constrained reverse repo facility does increase but is no longer constrained to be within 35bps of the base rate.

Interdealer rates for assets of which the central bank has plentiful supplies are floored at the facility rate, but rates may remain below this floor for assets where the central bank has little or no holdings of the asset. Transmission noise would fall by 9%.

Fourth, the effect of a facility depends on its pricing, as that determines the tightness of the constraint it imposes on repo rates. This can be seen in the effect of a reverse repo facility on monetary policy transmission in Table 10 and Figure 8. Pricing the unconstrained reverse repo facility at 5bps below the base rate achieves near perfect transmission, whilst doing the same for the constrained facility would have reduced transmission variability by 17% as opposed to the 9% for the more expensive facility.[39]

Fifth, the effect of these facilities would have varied materially over time, depending on the extent of collateral demand. Before January 2022, for example, collateral demand was low and both a reverse repo facility and a swap facility would have been little used, with minimal effects on outcomes. After this date, the facilities would have been widely used and had bigger effects.

7.2.3 Results: Surplus

Having described how such facilities would change trading behaviour, we now consider the extent to which they would improve surplus. We show the results for the constrained reverse repo facility (priced at 35bps below the base rate) and the constrained swap facility in Table 11. We show the surplus from repo trading earned by dealers, customers and the central bank, which we aggregate in two ways, to give a range of possible surplus outcomes.

The reverse repo facility involves dealers sending cash to the central bank, in return for desirable collateral and a repo rate paid by the central bank for the cash. We find that dealer surplus would increase by 48%. Customers do not have direct access to the facility,

[39] We do not show the effect of a facility priced at 75bps below the base rate (the current price for the facility offered by the DMO in the UK), but our simulations suggest it would barely have been used (consistent with its limited use in practice).

but their trading behaviour changes in a similar way to dealers: dealers have extra collateral and less cash relative to the baseline, and partially offset this by obtaining cash from and lending collateral to customers. This has a large, indirect effect on consumers that increases their surplus by 120%.

All that remains is to quantify the surplus, if any, earned by the central bank from this facility. The central bank receives cash in return for assets, and pays the facility rate to the dealers. We consider two ways of valuing these flows.

The first is to assume that any surplus earned by the bank is exactly offset by the repo rate that the central bank pays, making it indifferent between doing the transaction or not. In this case, aggregate surplus would simply be the sum of the dealer and customer surplus, implying a 54% increase.

The second approach is to attempt to specify central bank preferences. We assume the central bank has zero collateral demand, as it keeps the collateral on its balance sheet without any of the uses (from shorting, levering up or convenient sourcing of the bond) that drive collateral demand. We assume the central bank's funding demand is equal to the base rate. In this case, a reverse repo facility would generate large surplus that comes from the facts that (1) the central bank borrows cash at a discount relative to the base rate and (2) the central bank loses nothing by giving up the collateral. Aggregate surplus across all agents would increase very significantly by 170%. There could, of course, be other ways to specify central bank preferences, and we intend this result to make a simple point: such facilities could result in large surplus improvements because they transfer special collateral from central banks that do not value it to dealers that do.

Turning to the swap facility, this involves dealers exchanging assets with low collateral demand for assets with high collateral demand, at the cost of the payment for the facility. Given our assumption about pricing, this results in a small increase in surplus of dealers and a very small increase in surplus of customers. Turning to the central bank, we impose the same preferences as above: this means that the central bank is receiving a large payment in exchange for swapping two assets that it values equally (as it has zero collateral demand for all assets). The point of this surplus calculation is similar to that discussed above regarding the reverse repo facility: if central banks do nothing with the assets on their balance sheet and so value them equally, swapping them with dealers who do value them differently can involve very large surplus gains.

8 Conclusion

In this paper, we study the role of collateral demand in repo markets. We build a model of repo trade in which heterogeneous firms trade repo against multiple assets. We then estimate this using granular transaction data across firms and assets. We believe this to be the first structurally-estimated model of specialness. We use this estimated model to evaluate central bank facilities, which can inject supply of these assets that are in demand into these markets, and find that such facilities can improve surplus and monetary policy transmission.

Our data and setting are specific to the Sterling gilt repo market, but repo markets are important funding markets worldwide and there is evidence of collateral demand both in the US (Duffie, 1996) and in other European markets (Arrata et al., 2020; Ballensiefen et al., 2023), such that the issues we consider in this paper are of wider relevance. We leave for future work an assessment of how collateral demand impacts risk and financial stability, and a more comprehensive quantitative investigation of the feedbacks between repo markets and the cash markets for the underlying government bonds.

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Figures

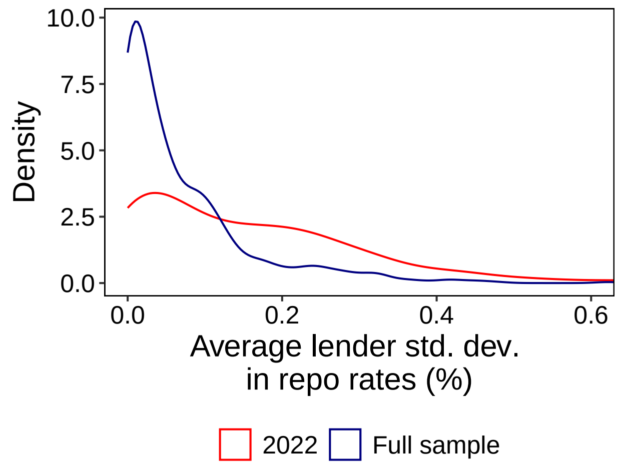


Figure 1: Distribution of Within-Lender Repo Rate Dispersion

Note: Figure shows how the repo rates that firms pay on their lending varies across firms. For each lender-date pair, we compute the standard deviation of the repo rates they pay, before averaging within lenders across dates. We then plot the distribution of this statistic across all firms, for the full sample (blue) and only for 2022 (red).

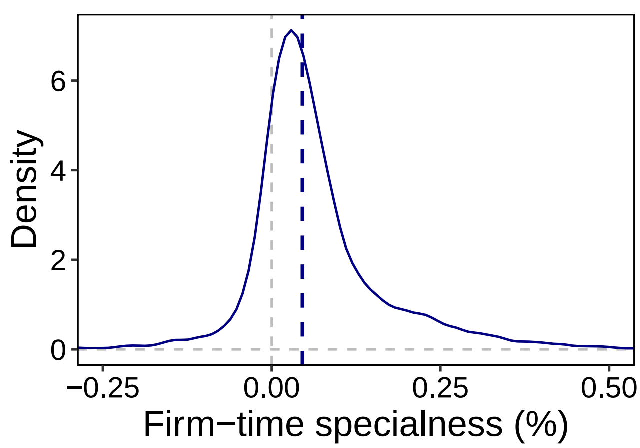


Figure 2: Lending specialness for general collateral borrowers

Note: Table summarizes the rate that traders who borrow against general collateral and lend against specific collateral pay for their lending. For every such trader on a given date, we compute the average rate on their lending against specific collateral, and subtract this from the average rate they pay on their general-collateral borrowing. A large positive number indicating the firm is paying a large price to obtain the specific collateral. We plot the density of this, with the dashed vertical line showing the median.

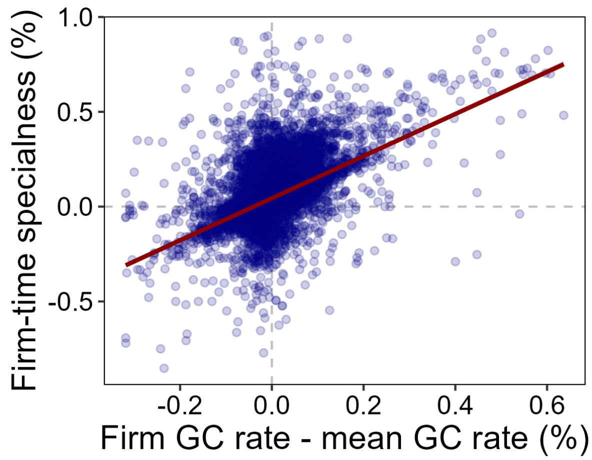


Figure 3: Specialness and general collateral rates

Note: Figure shows the relationship between the rates that a firm on a given date transacts at against general and specific collateral. Each point is a trade against both general and specific collateral on a given date. We compute firm-time level of specialness as the rate the firm pays on its general collateral activity minus its special collateral activity, and show this on the y-axis. The x-axis is the rate the firm pays on its general collateral minus the average general collateral rate on that date. The red line shows the line of best fit. We winsorize both variables at the 99.9% and 0.1% levels here, but the positive correlation is equally stark when we do not.

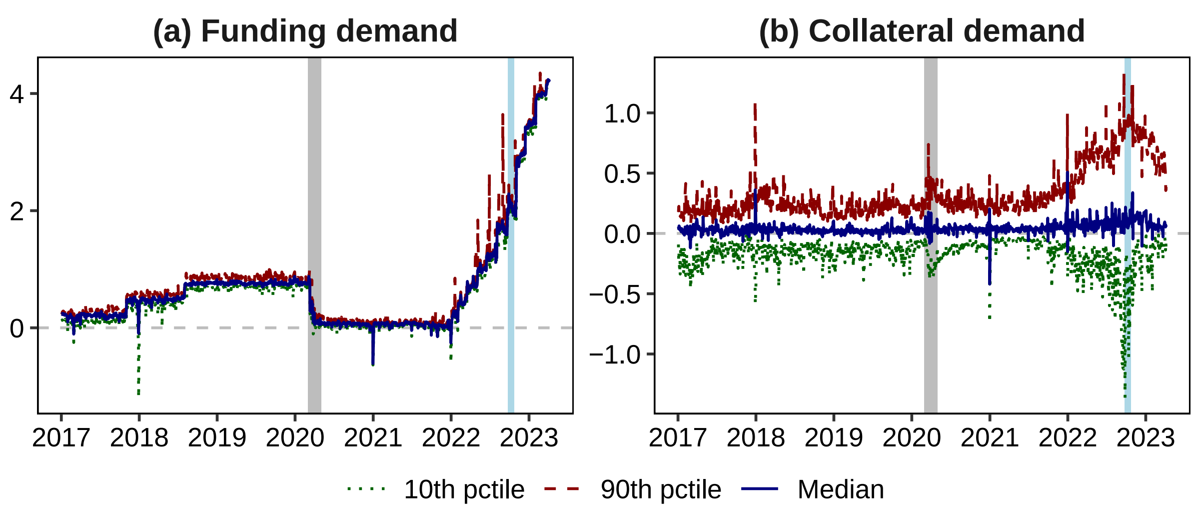


Figure 4: Funding & collateral demand through time

Note: Figure shows the distribution of funding demand ν_{it} across firms and time and of collateral demand η_{it}^{a} across firms, time and assets. The grey region highlights March & April 2020, around the 'dash for cash'. The blue region shows the month following 23$^{\text{rd}}$ September 2022, the beginning of the LDI crisis in the UK (Pinter, 2023).

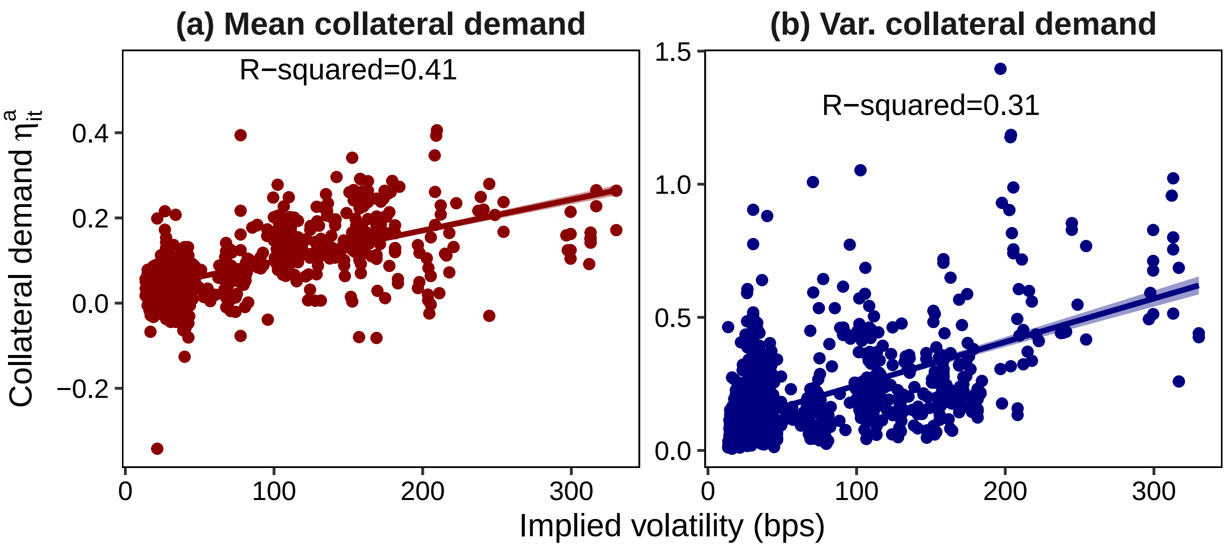
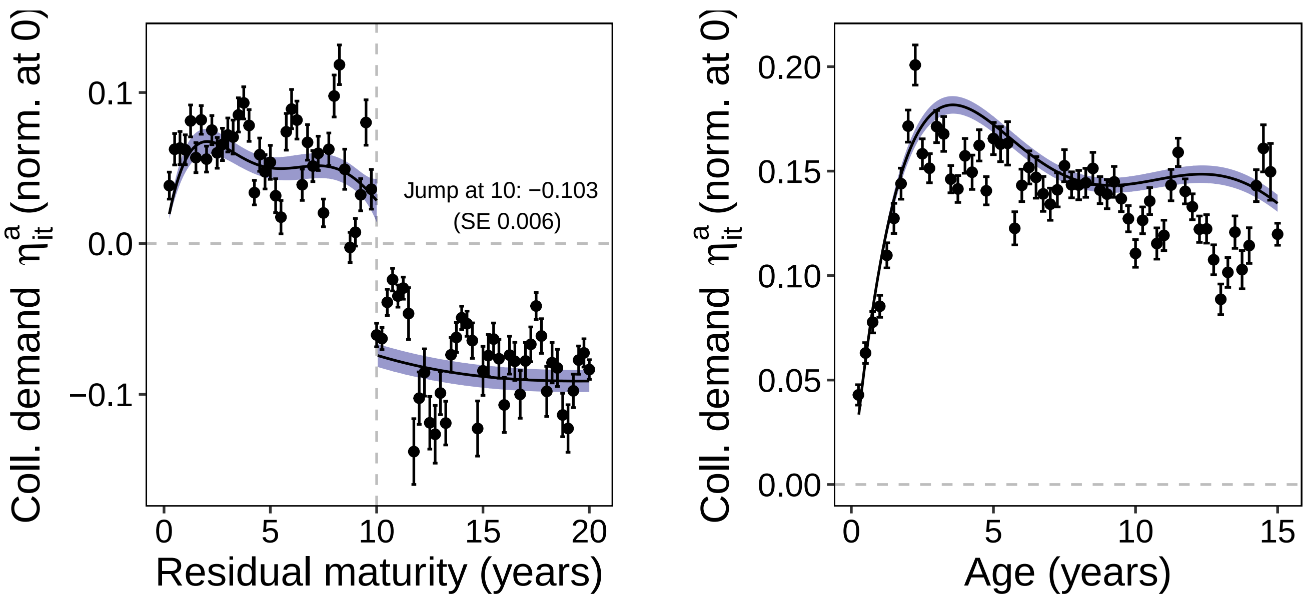


Figure 5: Gilt market volatility and collateral demand

Note: Figure plots the relationship between the daily swaption-implied volatility of interest rates, and the mean (left panel) and variance (right panel) of collateral demand η_{it}^{a} each day. Daily implied volatility of 1-year interest rates over a 3 month horizon are derived from UK interest rate swaption prices and taken from Bloomberg. The line shows a linear regression of the variable on the y axis on implied volatility, with 95% confidence intervals shown around this line of best fit.



(a) Bond residual maturity

(b) Bond age

Figure 6: Collateral demand and bond characteristics

Note: Table shows how collateral demand η^a_{it} varies with the residual maturity and age of bond a at time t. For the left-hand graph, we regress collateral demand on residual maturity buckets (in quarters), along with fixed effects and controls. For the right-hand graph, we regress collateral demand on age buckets (in quarters) along with fixed effects and controls. In both cases, we include date and firm fixed effects and a dummy for whether the bond is index-linked, and also control for the size of the float, defined as the amount in issuance minus the central bank's holdings. In the right-hand graph we also include a dummy for whether the bond is under 10 years from maturity, to strip out the maturity effects. Points show the estimated coefficients relative to the omitted category (under 1 quarter from maturity and under 1 quarter from issuance, respectively), with 95% confidence intervals around them. The smoothed lines show versions of the same regression with 5^{th} order polynomials, with a discontinuity at 10 years for maturity, and the area around shows a 95% confidence interval. Standard errors are clustered at the bond-date level.

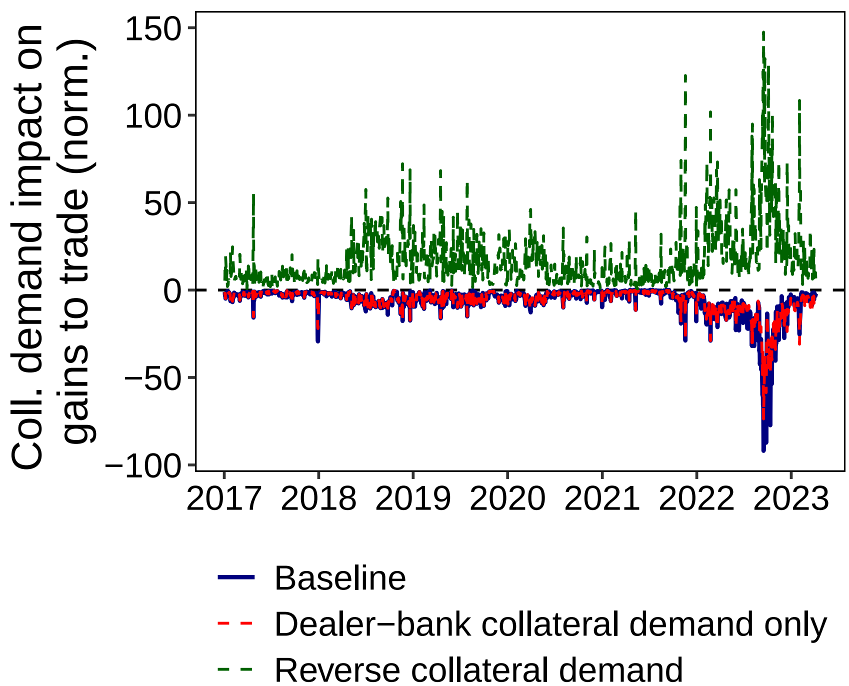


Figure 7: Counterfactual: impact of collateral demand – mechanisms

Note: Figure shows the impact of collateral demand over time under various bases. The blue solid line shows the difference between gains from trade in our baseline equilibrium and in our counterfactual equilibrium with zero collateral demand. The red dashed line shows the difference between gains from trade in our baseline equilibrium and in a counterfactual where dealers and banks have zero collateral demand, but all other firms' collateral demand is unchanged. To construct the green dashed line, we first rearrange collateral demand across firms to reverse the correlation between collateral demand and funding demand in Table 7. We then compute the difference between the gains from trade in this scenario and the gains from trade in the counterfactual with zero collateral demand. All series are normalized by the average gains from trade across our sample.

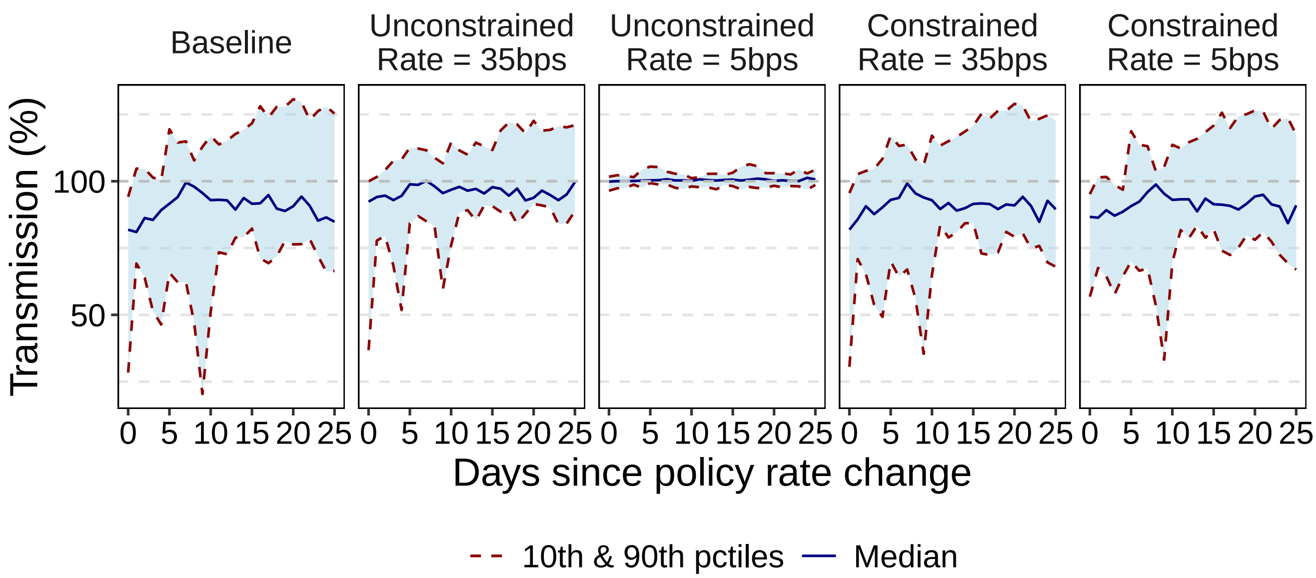


Figure 8: Monetary policy pass through with reverse repo facilities

Note: Figures show the transmission of monetary policy changes into average interdealer repo rates in our baseline (first panel) and for various implementations of a reverse repo facility (final panels). For a given monetary policy shift at date t, we compute the change in average rates from $t-2$ to $t+\tau$ as a percentage of the the change in the policy rate over the same period. We then take the median of this across all monetary policy changes for each $\tau = 1, ..., 25$ and plot this as the blue line in each graph. The red dashed lines show the 90^{th} and 10^{th} percentiles over each monetary policy change. To avoid transmission computations being polluted by term repo that incorporates expected rate changes, we compute it based on an estimation that only includes overnight and next day repo.

Tables

Table 1: Rate variation by lender sector

	Std. dev. (%) within date	Std. dev. (%) within date-borr.-mat.	Std. dev. (%) within date-borr.-mat.-lend.
Bank	0.13	0.06	0.06
Fund	0.10	0.04	0.04
Dealer	0.12	0.04	0.05
Hedge Fund	0.11	0.09	0.07
MMF	0.03	0.01	0.01
PFLDI	0.08	0.04	0.03
Other	0.10	0.07	0.07
Aggregate	0.12	0.06	0.05

Notes: Table shows variation in repo rates (net of the central bank base rate) by lending sector conditional on various features of the transaction. For example, to compute within-date standard deviation for banks, we take all repo lending by banks on a given date, compute the standard deviation of rates (net of the central bank base rate) across these transactions, and then average across all dates.

Table 2: Repo rates & collateral demand: MMFs vs hedge funds lending

	Repo rate net of Bank rate (%)		
	(1)	(2)	(3)
Constant	-0.08***		
	(0.009)		
Lender: Hedge fund	-0.13***	-0.10***	-0.08***
	(0.02)	(0.01)	(0.02)
R^2	0.04	0.43	0.52
Observations	370,645	370,645	368,793
Mean dep. var.	-0.19	-0.19	-0.19
Std. dev. dep. var.	0.11	0.11	0.11
Date fixed effects	No	Yes	No
Borrower-Date fixed effects	No	No	Yes

Notes: Table summarises the difference between the rates at which hedge funds and mutual funds lend. Each column shows the results of a regression of the repo rate (net of the central bank base rate) on the identity of the lender and a set of fixed effects, where the dataset consists only of transactions where the lender was either a hedge fund or a MMF. Standard errors are three-way clustered by firm, counterparty and date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 3: Net lending against general & specific collateral

	Borrow vs. specific coll	Lend vs. specific coll.
Borrow vs. general coll.	23.8	28.8
Lend vs. general coll.	14.2	33.3

Notes: Table summarizes firms' net lending against general and specific collateral. We take all firms that have non-zero net lending or borrowing against both general and specific collateral on any given date. Across these firm-date pairs, we then compute the percentage in each cell of the table. Central counterparties are excluded from this table.

Table 4: Parameter estimates: OLS and TSLS

	Repo rate r^a_{ijt} (%)	
	OLS	2SLS
	(1)	(2)
$\sum_l q^l_{ijt}$	-0.009**	-0.02**
	(0.004)	(0.008)
q^a_{ijt}	-0.13***	-0.18***
	(0.03)	(0.02)
Wald (1st stage), $\sum_l q^l_{ijt}$		96.2
Wald (1st stage), q^a_{ijt}		15.9
R^2	0.996	0.997
Within R^2	0.018	0.026
Observations	956,322	815,665
Firm-asset-day fixed effects	Yes	Yes
Firm-counterparty fixed effects	Yes	Yes

Notes: Table shows the results of estimating Equation 10. Standard errors are three-way clustered by firm-counterparty pair, asset, and date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 5: First stage results

	q^a_{ijt} (1)	$\sum_l q^l_{ijt}$ (2)
$z_{1,jt}$	-0.01***	-0.005***
	(0.002)	(0.0006)
$z^a_{2,jt}$	0.01***	0.0008*
	(0.002)	(0.0005)
R^2	0.80	0.94
Observations	815,665	815,665
Firm-asset-day fixed effects	Yes	Yes
Firm-counterparty fixed effects	Yes	Yes

Notes: Table shows the results of regressing the endogenous terms in Equation 10 on our instrumental variables, equivalent to the first stage in two-stage least squares estimation. $z_{1,jt}$ and $z^a_{2,jt}$ are the instruments detailed in Section 5. Standard errors are three-way clustered by firm-counterparty pair, asset and date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 6: Funding and collateral demand by sector

	Funding demand ν_{it} (1)	Collateral demand η^a_{it} (2)
Bank	0.01***	-0.0004
	(0.0008)	(0.0010)
Dealer	0.12***	0.13***
	(0.002)	(0.001)
Fund	-0.01***	-0.04***
	(0.0006)	(0.001)
Hedge Fund	0.008***	0.03***
	(0.0008)	(0.001)
MMF	-0.07***	-0.03***
	(0.001)	(0.001)
PFLDI	-0.004***	-0.19***
	(0.001)	(0.001)
R^2	0.98	0.11
Observations	203,000	2,504,327
Mean dep. var.	0.76	0.12
Std. dev. dep. var.	0.15	0.30
Date fixed effects	Yes	Yes

Notes: Table shows variation in funding and liquidity demand across firms. We regress our panel of estimated values of funding demand ν_{it} (first column) and collateral demand η^a_{it} (second column) on dummies for the type of firm i and date fixed effects. The omitted category is 'other' firms, which includes insurers, principal trading firms and central banks, along with other firm types. We exclude central counterparties from these regressions. Standard errors are clustered at the date level in the first column, and the bond-date level in the second. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 7: Collateral & Funding Demand

	Collateral demand η^a_{it}			
	(1)	(2)	(3)	(4)
Constant	0.02***			
	(0.0006)			
Funding demand ν_{it}	0.11***	0.90***	0.07***	0.89***
	(0.0010)	(0.0007)	(0.0008)	(0.0007)
R^2	0.12	0.65	0.49	0.67
Observations	2,504,327	2,504,327	2,504,327	2,504,327
Mean dep. var.	0.12	0.12	0.12	0.12
Std. dev. dep. var.	0.30	0.30	0.30	0.30
Date fixed effects	No	Yes	No	No
Firm fixed effects	No	No	Yes	No
Sector-Date fixed effects	No	No	No	Yes

Notes: Table summarises the co-movement between collateral demand and funding demand. We regress our panel of estimated values of collateral demand η^a_{it} on funding demand ν_{it}, together with the relevant fixed effects. Standard errors are clustered at the asset-time level. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 8: Collateral demand and asset characteristics

	Collateral demand η_{it}^{a} (1)
log asset float	-0.10***
	(0.001)
1st off run	0.002**
	(0.0009)
2nd off run	-0.02***
	(0.002)
3rd off run	-0.08***
	(0.002)
4th off run	-0.13***
	(0.004)
R^2	0.55
Observations	2,288,660
Maturity controls	Yes
Age controls	Yes
Mean dep. var.	0.12
Std. dev. dep. var.	0.30
Date fixed effects	Yes
Firm fixed effects	Yes
Bond type fixed effects	Yes

Notes: Table shows how collateral demand varies with the size of the float, and whether the bond is on-the-run. Age controls are a fifth-order polynomial in age, whilst maturity controls denote a dummy for whether the bond is under ten years from maturing. A bond's type denotes whether it is index-linked or not. An asset's float is the amount in issuance minus the central bank's holdings, measured in £bn. Central counterparties are excluded from this table. A bond is X places off-the-run at time t if there have been X bonds with the same maturity year issued after the bond in question. The omitted category is on-the-run bonds. Standard errors are clustered at the bond-time level. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table 9: Counterfactual: impact of collateral demand

	Collateral demand	No collateral demand
Mean repo rate (bps)	-14.3	-9.3
Std. dev. repo rate (bps)	8.0	6.6
Trading quantity (£bn)	106.4	322.0
Gains from trade	1.0	6.8

Notes: Table summarizes the effect of collateral demand on market outcomes. The first column shows outcomes in our estimated equilibrium, whilst the second shows these same outcomes in a counterfactual simulation where collateral demand is zero for all assets, firms and dates. To compute the mean and standard deviation of rates, we first compute the average rate (net of the central bank base rate) for each asset on each date. We then average across assets and then across dates to compute the mean rate, and take the standard deviation across assets before averaging across dates to get the standard deviation.

Table 10: Counterfactual: central bank facilities

	Baseline	Reverse repo facility				Swap facility	
		Unconstrained		Constrained		Unconstrained	Constrained
		35bps	5bps	35bps	5bps	70bps	70bps
Before January 2022							
Mean rate (bps)	-9	-8	-1	-9	-3	-9	-9
Std. dev. rate (bps)	5	5	3	5	4	5	5
Min. interdealer rate (bps)	-34	-28	-5	-32	-24	-33	-34
Range interdealer rate (bps)	32	27	10	31	26	31	32
Volume (£bn)	101	105	223	103	177	102	101
Facility usage (£bn)	0	6	153	4	103	1	0
January 2022 onwards							
Mean rate (bps)	-38	-10	9	-25	-17	-38	-38
Std. dev. rate (bps)	20	15	13	18	17	17	19
Min. interdealer rate (bps)	-134	-35	-5	-120	-112	-100	-132
Range interdealer rate (bps)	130	54	42	126	126	64	119
Volume (£bn)	130	846	1331	427	616	928	156
Facility usage (£bn)	0	673	1144	310	503	599	23
Aggregate							
Median transmission (%)	91	96	100	91	91	92	91
Transmission noise (%)	53	32	5	48	44	52	52

Notes: Table summarizes the effect of central bank facilities on various outcomes. Each column corresponds to a different type of facility. The first column shows our baseline with no facility. The next four columns show reverse repo facilities, and the final two show swap facilities. We show reverse repo facilities priced at 35bps and 5bps below the central bank base rate, and swap facilities with a price of 70bps (chosen to correspond to twice the price of the reverse repo facility). A constrained facility is one where the central bank can only lend out as much of an asset as it holds on its balance sheet. To compute the mean and standard deviation of rates, we first compute the average rate (net of the central bank base rate) for each asset on each date. We then average across assets and then across dates to compute the mean rate, and take the standard deviation across assets before averaging across dates to get the standard deviation. The minimum interdealer rate is the minimum across assets (net of the base rate), which we then average across dates. The range is computed across assets within a date, then averaged across dates. Trading quantity is the total amount traded in the interdealer market, the dealer-customer market and, if applicable, with a facility. Usage is the amount traded with the facility. Transmission and transmission noise are defined in Section 7.2.2. To avoid transmission computations being polluted by term repo that incorporates expected policy rate changes, we compute it based on an estimation that only overnight and next day repo.

Table 11: Surplus with central bank facilities

Surplus	Baseline	Reverse repo facility	Swap facility
(1) Dealers	0.90	1.33	0.93
(2) Customers	0.10	0.22	0.10
(3) Central bank	0.00	1.16	0.90
Total surplus			
(1)+(2)	1.00	1.54	1.03
(1)+(2)+(3)	1.00	2.70	1.93

Notes: Table summarizes the effect of a reverse repo facility (priced at 35bps below the central bank base rate) and a swap facility (priced at 70bps) on surplus. All values are normalized by the level of total surplus in the baseline. Computations are described in Section 7.2.3.

A Market features and summary statistics

We discuss (1) transaction characteristics, (2) bond characteristics, (3) trading behaviour by different types of firm, (4) the level of the repo rates, (5) drivers of the repo rate, (6) the trading network, (7) general collateral and (8) monetary policy transmission.

Transaction characteristics. We describe mean transaction characteristics in Table A1. Most repo transactions are short maturity, as set out in Table A1: three-quarters of repos have maturity of one day. Dealers and banks trade with each other and with customers, and there is no inter-customer trade. Our data on haircuts is incomplete and relatively low quality, but over 80% of transactions are reported as involving a haircut of 0.

Bond characteristics We have 115 bonds in our dataset. Table A2 summarizes the sample of bonds which serve as collateral in our data. For each bond-date pair that appears in our dataset, we summarize the distributions of key variables describing the amount of the bond that is in issue, how much is held by the central bank, how much is traded via repo, and the rate at which these repos take place.

We highlight two key patterns for our paper. First, the Bank of England's quantitative easing operations mean that on average in our sample around 20% of the issuance of a bond is held on a bank's balance sheet, though there is significant heterogeneity across bonds. In Section 7 we study the effects of making these bonds available to the market.

Second, across all dates in our sample, the average bond trades at a repo rate 8bps below the central bank's base rate. There is significant variation in this, however, with some trading significantly lower and some trading at a premium relative to the central bank's policy rate. Our estimation will unpack the drivers of this heterogeneity across firms, assets and time.

Trading behaviour We have 1070 distinct traders in our dataset. Participants in the gilt repo market include dealers, banks, hedge funds, money market funds, mutual funds, insurers, pension funds and other types of firm. In Table A3 we show their trade shares, and their daily net lending in both percentage and absolute terms. In what follows we will highlight the differing behaviour of dealers, hedge funds and money market funds (MMFs). These sets of firms are of particular interest to our analysis as their business models imply specific patterns of collateral demand.

Dealers participate in this market to obtain both funding and collateral. Cash and securities may be used for the dealers' own activities or is being sourced for their clients. Dealers also intermediate on behalf of their clients, thus trading with many more counterparties than any other type of firm. Table A4 shows the rates dealers earn on their repo lending vs their borrowing. Dealers earn a spread, both in aggregate and within assets and time periods. This is consistent with Huber (2023) and Eisenschmidt et al. (2022), who find that dealers enjoy market power in US and European repo markets respectively.

In Figure A2 we show how this spread that dealers earn varies with the characteristics of the customer with whom they are trading. In particular, we take the final specification in Table A4 and interact the regressor with the number of counterparties with whom the dealer trades. We plot these coefficients in Figure A2. Whilst there is some noise around our estimates, the downward trend suggests that dealers' market power with respect to customers declines as their customers are less connected.

MMFs are almost uniquely lenders in repo markets (Table A3). MMFs are mutual funds that invest in low-risk, short-term (typically government) securities. MMFs keep a fraction of their assets invested in cash. They lend this cash out as repo as it earns them a return but remains a safe investment as it is collateralized. The collateral they receive is pure risk mitigation or insurance against the counterparty's default. They typically do not short sell assets and nor trade derivatives. As a result the collateral demand motive for trading repo is missing for these firms.

Hedge funds play a very different role. As shown in Table A3, their activities are roughly balanced between lending and borrowing. This is because repo serves a dual purpose for hedge funds: they use repos in order to fund their activities (Barth and Kahn, 2021), but also in order to obtain the asset, for example to short it (Adrian et al., 2013). For example, a hedge fund following a strategy of yield curve arbitrage looks to take long and short positions at different points on the yield curve, and may use repo to implement its short positions. For hedge funds, then, obtaining collateral is not just for risk mitigation, but also represents their demand for securities.

Rate level. Figure A1 shows the rates dealers earn on their repo lending, together with the rate paid on reserves at the Bank of England. If the only benefit to repo lending for dealers was to earn a return, they should not lend at a lower rate than that which they can earn risk-free by placing their money with the central bank. As Figure A1 shows, dealers frequently lend in the repo market at rates below Bank rate, as documented by Arrata et al. (2020). This can only be rationalised if repo lending is about more than just earning a return, but is also about obtaining the collateral.[40]

[40]Note that the very narrow difference between repo rates and the central bank rate suggest concerns about creditworthiness are only minor determinants of repo rates.

Rate drivers. Table A5 provides evidence on the role of collateral demand. We regress the repo rate (net of the central bank's policy rate) on various combinations of fixed effects. The first set describe the terms of the transaction taking place: the collateral being pledged and the maturity of the lending relationship. If two firms are offering to lend for the same maturity against the same bond at the same time, they are in effect offering the same contract. The second set of fixed effects describes who is writing the contract.

For trades in a given week, the repo rate is determined in large part by which bond is provided as collateral. These bonds are claims on the same issuer – the UK government – who has essentially no risk of default, and the repo contracts themselves tend to be of very short maturity (Table A1) and thus themselves face very little risk of default. It is therefore unlikely that the differences in repo rates across different bonds capture differences in their value as insurance in case of default. It is much more consistent with the idea that at certain times certain bonds are desirable, that repo is a way to obtain these bonds, and traders are willing to pay higher rates to obtain them.

Trading network. The network of trading relationships is sparse, and the creation of wholly new links relatively rare. Fewer than 2% of counterparty pairs have non-zero trade in the whole sample. Over 95% of transactions after January 2022 were between traders who had traded together before January 2022.

Table A6 gives more details on the structure of the network. For each firm, we count the number of unique counterparties with which they trade across our whole sample period. We then summarize this statistic for each firm sector in the first panel of the table. In the second panel, we compute the share of each trader's trading volume that is with their largest counterparty, and again summarize this statistic's distribution across sectors.

Dealers have a large number of counterparties and spread their trade across these counterparties. Other sectors often only have a few counterparties and rely on one key counterparty for a lot of their repo trading, though there is heterogeneity both within and across traders.

In Table A7, we summarize the persistence of links. In each year, we compute the number of unique links between pairs of firms. We then compute *new links*—the percentage of a year's network links that did not appear the year before—and *disappeared links*—the percentage of last year's network links that did not appear this year, and average across years. We then compute weighted versions of these statistics, where *new links* now measures the percentage of trading volume in a year that is on new links, and *disappearing links* measures the proportion of last year's trading that was on links no longer present this year.

Finally, we reproduce these calculations at the monthly frequency.

As can be seen in Table A7, links do appear and disappear between periods, but the majority last from year to year. When we weight by trading volume, the significant majority of links are stable. There is more variability from month to month, presumably representing idiosyncratic trading needs.

Together, these patterns suggest that (a) there is a clear network structure in our data, (b) the creation of wholly new links is not a major source of variation in our data, and (c) most trading takes place on links that endure from period to period. Guided by these facts, in our modelling and counterfactuals, we will take the network of trading relationships that we observe on a given date as given.

General collateral. Firms trade repo against both general and specific collateral. Across our whole sample period, around 9% of aggregate repo trading is against general collateral, where the collateral exchanged can be any of a pre-specified set of bonds. We will use the simultaneous trading of general and specific collateral repo to separately identify funding demand and collateral demand in Section 5.

As in Ballensiefen et al. (2023), we find that rates differ for general and specific collateral in a way that is consistent with collateral demand: borrowing against a specific bond is cheaper than borrowing against a set of bonds (Table A8). We interpret the coefficient in Table A8 as capturing the value of receiving specific collateral in a repo.

Monetary policy transmission: We measure the transmission of monetary policy by comparing changes in the base rate and subsequent changes in the mean interdealer repo rate. For each monetary policy event, we calculate the change in the repo rate as a percentage of the change in the base rate for various intervals of time after the base rate change. If this is not 100%, then passthrough is imperfect. We plot the distribution of this measure across monetary policy events in Figure A3 and show that there was material noise in transmission over our sample.

B Cross-checks

B.1 Cross-check: Identifying variation

The way in which our estimation approach maps empirical variation in transaction characteristics into estimated variation in structural parameters is clear from Equation 15. Both collateral demand and funding demand are pinned down by variation in repo rates and variation in repo quantities. We now demonstrate empirically the extent to which our estimates are driven by rate variation vs. quantity variation.

To do so, we regress our empirical estimates of funding demand ν_{it} and collateral demand η_{it}^{a} on variables involving repo rates and quantities motivated by Equation 15, along with fixed effects. We then show the proportion of the variation in our parameter estimates – after stripping out the fixed effects – that can be explained by the regressors. Table A9 shows the variables and fixed effects we include, together with the within-R-squared, defined as the proportion of the variation in the dependent variable left over after stripping out the fixed effect that can be explained by the regressor.

The time series variation in funding demand is overwhelmingly driven by changes in the rates at which firms trade general collateral repo. By contrast the across-firm variation is driven by differences in firms' net borrowing: firms with high collateral demand are those that borrow large amounts via repo. The across-asset variation in collateral demand is largely driven by repo rates: assets that in aggregate have high collateral demand are those that trade at a discount relative to the general collateral rate. By contrast, most of the across-firm variation is driven by trading quantities: firms with high collateral demand for a given asset a are those that lend large amounts against a relative to their lending against general collateral. Time series variation is driven by both rate and quantity variation.

B.2 Cross-check: Reduced-form vs structural results

The standard approach to studying collateral demand – alternatively specialness – is to compare rates on repos for specific assets to rates on repos for a more general basket of collateral. If repo for a specific asset trades at a discount rate relative to general collateral, this indicates there is an unusually high level of demand for that asset as collateral.

Our estimation of collateral demand has two innovations relative to this existing approach: it is firm-specific and it is supported by a model. The advantage of the former is that it allows us to understand how asset-level collateral demand is driven by firm-level demands. The advantages of the latter are twofold: it allows us to control for confounding factors like market power or the structure of the network, and it allows us to use quantity data to identify collateral demand as well as rate data. For example, if firm A borrows a large amount against general collateral from firm B, but also lends to firm B against a specific gilt, this would suggest that firm A has collateral demand for that specific gilt. Our estimation approach harnesses this identifying variation as well as rate variation.

In Table A10 we summarise the extra information we get from our estimation approach relative to the approach taken in the literature. In the first column we regress our estimated collateral demand η_{it}^{a} on the average difference between the repo rates on asset a at time t and the general collateral repo rate at time t. This regressor is an example of the standard asset-level rate-based approach to estimating collateral demand. The coefficient estimate is 1: the two approaches are clearly capturing many of the same features. However, the R-squared is under 20%: the standard approach captures only a small proportion of the variation in our more granular estimates. This suggests that there is potentially significant value to estimating collateral demand at the firm level.

In the second column we regress our estimated collateral demand on a firm-level version of the standard approach. Here the regressor is the average difference between the repo rates on asset a by firm i at time t and the general collateral repo rate of firm i at time t. Once again, it is clear the two estimates share common variation, but our estimates contain a lot of variation that cannot be captured by the more standard approach, even when applied at the firm level. This suggests that there is potentially significant value to using repo quantities, as well as rates, to estimate collateral demand.

C Robustness

In this Section we show the robustness of our main results along the following dimensions: (1) whether we estimate our model solely using overnight and next day repo rather than all repo, (2) whether collateral demand varies depending on whether it is incoming or outgoing for a given firm, (3) how we weight the bonds in our instrumental variable, (4) allowing our curvature parameters κ and σ^2 to vary through time, and (5) omitting the ten most traded bonds from our estimation.

In each case, we flex the relevant assumption and show how this affects our estimates of:

- The regression yielding our curvature parameters κ and σ^2 (Table A11).
- The times series of funding demand ν_{it} and collateral demand η_{it}^{a} (Figures A4 to A8).
- Funding demand ν_{it} and collateral demand η_{it}^{a} across sectors (Tables A12 and A13).

We do not display the results of counterfactuals under these alternative assumptions, but given the robustness of our results along the dimensions we do show, the results of these counterfactuals will be in general be similar.

C.1 Repo maturity

As a test of the robustness of our results to alternative assumptions regarding repo maturity, we re-run the estimation using only the shortest term repos: overnight repos and next day repos. Our estimation of the market power terms is in the second column of Table A11. The time series of funding and collateral demand through time is in Figure A4. The patterns of funding demand and collateral demand across sectors are in the second column of Table A12 and second column of Table A13 respectively.

Our estimated funding and collateral demands under this alternative approach are very similar. The coefficients on the market power terms in Table A11 have changed relative to the baseline, implying a lower risk aversion parameter κ but a higher risk parameter σ^2. As can be seen from Equations 8 and 10, the effects of these movements in κ and σ^2 on rates and quantities partially offset each other. We have checked the robustness of each of the facility counterfactuals to this assumption, and find that the results are very similar.

C.2 Incoming and outgoing collateral

In our baseline approach we allow collateral demand to vary at the time-firm-asset level, but not to vary according to whether the firm is borrowing or lending. Here we examine whether collateral demand varies along this dimension in a way that matters for our results.

We do this by including a firm-direction dummy variable in the first step of our estimation:

$$r^a_{ijt} = \delta^a_{it} + \underbrace{\delta_i \times \mathbb{1}_{q^a_{ijt}>0}}_{\text{Outgoing dummy}} - \left[\kappa \sum_l q^l_{ijt} + \kappa\sigma^2 q^a_{ijt}\right] \mathbb{1}_{ij} + \delta_{ij} + u^a_{ijt} \tag{C1}$$

where $\mathbb{1}_{q^a_{ijt}>0}$ is a dummy variable that takes the value 1 if firm i is borrowing (indicating that the collateral is outgoing) and δ_i is the firm-specific parameter on that dummy variable. This effectively asks whether a given firm systematically lends and borrows against the same asset at different rates, holding constant the determinants of the intermediation spread.

In Figure A5a we show the distribution of estimated collateral demand conditional on whether a firm is borrowing or lending cash. The distributions are very similar. In Figure A5b we plot the time series of collateral demand. The patterns are very similar to our baseline estimates in Figure 4. Finally, in the third column of Table A12 and the third column of Table A13 we show the estimated average funding and collateral demand across firm types respectively. Again, the results are similar.

C.3 Instrumental variables

In this section, we set out results that adjust the definition of our instrumental variables. Identification of step 1 of our baseline estimation requires that the unobserved shocks are independent of our instrument constructed by interacting bond prices with firm-specific lagged trading across bonds (which, as described in Section 5, we term the firm's wallet). The motivation for this approach is that firms trade specific bonds for exogenous reasons related to their business or preferred habitat, and that changes in price to these specific bonds shock a given firm's trading independently of unobserved shocks in the repo market.

In this test, we change how we weight bond prices in our instrumental variables. In our baseline, we calculate the sum of firm j's borrowing in time $t-1$ against asset j, which we denote s^a_{jt-1}. We use this variable to weight bond prices $price^a_t$ and calculate our instrumental variables, as set out in Equations 12 and 13. In this robustness test, we homogenise the weighting across bonds:

$$\tilde{s}_{jt-1} = \frac{\sum_a s^a_{jt-1}}{\sum_a 1} \tag{C2}$$

$\tilde{s}_{jt-1}$ is thus the average amount traded by j across bonds. We then use this in place of s^a_{jt-1} to construct our instruments in Equations 12 and 13. This alternative approach guards against serial correlation in bond-specific unobservable reasons for trade.

Whilst the curvature parameters are individually materially different (and in one case marginally negative and insignificant, as in the fourth column of Table A11) our main objects of interest – estimated funding and collateral demands – under this alternative approach are very similar, both in the time series (Figure A6) and in the cross section (fourth columns of Table A12 and Table A13, respectively. This suggests that the changes to the two curvature parameters largely net out.

C.4 Omitted collateral

Whilst our dataset includes close to the universe of trading in sterling government bonds, and the significant majority of UK repo is backed by government bonds, firms in our data will also trade repos backed by other collateral, notably corporate bonds.[41] We do not have

[41] Julliard et al. (2023), for example, find that between 4% and 6% of the total UK repo market is backed instead by corporate debt and between 1% and 7% by securitized products. The remainder is backed by government debt.

data on repo backed by other types of asset, but instead we undertake an additional test to demonstrate the robustness of our results to omitting certain assets. We delete the ten most traded bonds in our sample, representing 23% of the market, and re-run estimation.

In the fifth column of Table A11 we show that our estimates of the market power terms are similar to the baseline, implying similar estimates of κ and σ^2. In Figure A7 we show that the time series of estimated funding and collateral demand are similar under this alternative approach. Similarly, the cross-sectional results are similar (fifth columns of Table A12 and Table A13 respectively) are very similar. This is because identification of these values is based primarily on comparisons of trade in a given asset with trade in general collateral, as can be seen from Equation 15.

C.5 Heterogeneous curvature parameters

In our baseline specification the risk associated with temporary use of the collateral, σ^2, is constant across firms, time and assets, and so is curvature parameter κ. In principle, variation along these dimensions is identifiable. Here we estimate κ and σ^2 separately by year, constraining them to be between half and twice their estimated size in the baseline.

We plot the times series of funding and collateral demand in Figure A8. The shape of the two time series is similar to our baseline results, albeit with the dispersion of collateral demand higher in 2017 than in the baseline. In the sixth columns of Table A12 and Table A13 we show the estimated average funding and collateral demand across firm types, replicating the analysis shown in Table 6. Again, the results are similar.

D Derivation of Equilibrium Equations with Facilities

D.1 Reverse repo facility: unconstrained

With access to a central bank reverse repo facility, a dealer's payoff function is as follows:

$$U_d \equiv \nu_d(Q_d - L_d) - \frac{\kappa}{2}(Q_d - L_d)^2 - \sum_a \eta_d^a(Q_d^a - L_d^a) - \sum_a \frac{\kappa}{2}\sigma^2(Q_d^a - L_d^a)^2 - \\ \sum_a \Big(\sum_{m \in \mathcal{N}_d^a} q_{dm}^a(r_{dm}^a + \epsilon_{dm}^a) - L_d^a(r_{CB}^a + \epsilon_{d,CB}^a)\Big),$$

where $L_d^a \geq 0$ is the amount of asset a that d receives via the facility in exchange for cash, and L_d is the sum of L_d^a across assets.

Lending to the facility against asset a reduces a dealer's net cash borrowed, but boosts the amount of asset a it has acquired. We assume that the structural error for obtaining asset a from the central bank is the same as from the interdealer market: $\epsilon^a_{d,CB} = \epsilon^a_{dD}$.

The marginal benefit of L^a_d is:

$$\frac{\partial U_d}{\partial L^a_d} = -\nu_d + \kappa(Q_d - L_d) + \eta^a_d + \kappa\sigma^2(Q^a_d - L^a_d) + \epsilon^a_{dD} + r^a_{CB}.$$

Straightforward algebra shows that:

$$\frac{\partial U_d}{\partial L^a_d} + \frac{\partial U_d}{\partial q^a_{dD}} = r^a_{CB} - r^a_D.$$

This implies that:

1. If the central bank reverse repo rate is higher than the interdealer rate, a dealer can make infinite profit by borrowing at the interdealer rate, lending to the facility, and earning the spread. Thus in any equilibrium $r^a_D \geq r^a_{CB}$.

2. If the central bank reverse repo rate is strictly lower than the interdealer rate for an asset, the facility will not be used by any dealer: $L^a_d = 0 \ \forall d = 1, ...N_D$.

3. If $r^a_D = r^a_{CB}$ then q^a_{dD} and L^a_d are not separately pinned down. As a result, for the rest of this section we subsume dealer d's interdealer trading and its trading with the central bank as q^a_{dD}. By definition of the reverse repo facility and the fact that direct trading between dealers must net out, it follows that aggregate dealer borrowing from other dealers and the central bank against asset a must be weakly negative.

This implies that the following are all necessary conditions in equilibrium:

$$\sum_{d=1}^{N_d} q^a_{dD} \ \leq \ 0, \quad r^a_D \geq r^a_{CB}, \quad (r^a_D - r^a_{CB}) \sum_{d=1}^{N_d} q^a_{dD} = 0 \quad \forall a.$$

Intuitively, the facility is a perfect substitute for lending to other dealers, so no dealer would lend at a dominated rate. This means the facility rate places a floor on the interdealer rate. If this floor does not bind for asset a, no dealer will use the facility to obtain asset a.

In Online Appendix O2, we show that these conditions, together with the first-order conditions in equations 4, 5 and 6, define a unique equilibrium that always exists. The equilibrium conditions are now nonlinear, so we solve for the equilibrium numerically.

D.2 Reverse repo facility: constrained

We now consider a constrained reverse repo facility, where the amount dealers can borrow of an asset from the facility is limited by central bank holdings h^a_{CB}. The perfect substitutability between interdealer repo and the facility still holds. Now, however, dealers can only take advantage of the facility up to its limit. As a result:

- The interdealer rate for asset a can only be strictly below the facility rate if dealers have borrowed as much of asset a as they can.
- As before, if the central bank reverse repo rate is strictly lower than the interdealer rate, the facility will be unused.
- As before, dealer d's interdealer activity in a and its dealings with the facility are not separately pinned down, so we refer to d's aggregate net borrowing of a across the interdealer market and the facility as q^a_{dD}.

The conditions governing the choice between interdealer activity and the facility are now:

$$-h^a_{CB} \;\leq\; \sum_{d=1}^{N_d} q^a_{dD} \;\leq\; 0 \tag{D1}$$

$$r^a_D \begin{cases} = r^a_{CB}, & \text{if } -\, h^a_{CB} \;<\; \sum_{d=1}^{N_d} q^a_{dD} \;<\; 0, \\ \geq r^a_{CB}, & \text{if } \sum_{d=1}^{N_d} q^a_{dD} \;=\; 0, \\ \leq r^a_{CB}, & \text{if } \sum_{d=1}^{N_d} q^a_{dD} \;=\; -\, h^a_{CB}. \end{cases} \tag{D2}$$

The first condition is the feasibility constraint, which says the facility cannot lend out more of an asset than the central bank holds. The cases for r^a_D are the optimality conditions that follow from the perfect substitutability, together with the upper and lower bounds on usage of the facility.

In Online Appendix O2, we show that these conditions, together with the first-order conditions in equations 4, 5 and 6, define a unique equilibrium that always exists. The equilibrium conditions are nonlinear, so we solve for the equilibrium numerically.

D.3 Swap facility: unconstrained

With a swap facility, the utility to dealer d is now:

$$U_d \equiv \nu_d Q_d - \frac{\kappa}{2} Q_d^2 - \sum_a \eta_d^a \big(Q_d^a - \sum_{a'} S_d^{a,a'}\big) - \sum_a \frac{\kappa}{2}\sigma^2 \big(Q_d^a - \sum_{a'} S_d^{a,a'}\big)^2 \\ - \sum_a \Big(\sum_{m \in \mathcal{N}_d^a} q_{dm}^a (r_{dm}^a + \epsilon_{dm}^a) + \sum_a \sum_{a'} \max\{S_d^{a,a'}, 0\}(r_{CB} + \epsilon_{d,CB}^{a,a'})\Big),$$

where $S_d^{a,a'}$ is the amount of a that dealer d receives from the swap facility in exchange for a', $S_d^{a,a'} = -S_d^{a',a}$, and $\epsilon_{d,CB}^{a,a'}$ is a non-pecuniary cost to dealer d from using the facility to exchange a and a'.

Swapping asset a for a' leaves dealer d's cash position unchanged, but affects the net amounts of a and a' that the dealer has acquired. The cost of the facility - which we assume is constant across assets - subtracts from the firm's utility.[42]

Take the case where $S_d^{a_1,a_2} > 0$, and consider the marginal benefit of increasing $S_d^{a_1,a_2}$:

$$\frac{\partial U_d}{\partial S_d^{a_1,a_2}} = \eta_d^{a_1} - \eta_d^{a_2} + \kappa\sigma^2 (Q_d^{a_1} - \sum_{a'} S_d^{a_1,a'}) - \kappa\sigma^2 (Q_d^{a_2} - \sum_{a'} S_d^{a_2,a'}) - (r_{CB} + \epsilon_{d,CB}^{a,a'}).$$

Simple algebra shows:

$$\frac{\partial U_d}{\partial q_{dD}^{a_2}} - \frac{\partial U_d}{\partial q_{dD}^{a_1}} = \eta_d^{a_1} - \eta_d^{a_2} + \kappa\sigma^2 (Q_d^{a_1} - \sum_{a'} S_d^{a_1,a'}) - \kappa\sigma^2 (Q_d^{a_2} - \sum_{a'} S_d^{a_2,a'}) - (r_D^{a_2} + \epsilon_{dD}^{a_2}) + (r_D^{a_1} + \epsilon_{dD}^{a_1}).$$

For simplicity, we assume that the non-pecuniary benefits that a dealer gets from exchanging two assets via the interdealer market are the same as via the facility. As a result:

$$\frac{\partial U_d}{\partial S_d^{a_1,a_2}} - \left(\frac{\partial U_d}{\partial q_D^{a_2}} - \frac{\partial U_d}{\partial q_D^{a_1}} \right) = (r_D^{a_2} - r_D^{a_1}) - r_{CB}.$$

[42] We take the maximum of $S_d^{a,a'}$ and 0 to avoid double counting: if a dealer obtains $S_d^{a,a'}$ of asset a in return for giving $S_d^{a,a'}$ of asset a' to the facility, they pay only $r_{CB} S_d^{a,a'}$.

It follows that:

- If the difference between two assets' repo rates is greater than the facility rate, dealers can earn infinite revenues by swapping assets using the facility (at a cost of the facility rate) and swapping them back on the interdealer market (gaining the rate difference). It follows that in equilibrium $r_D^a - r_D^{a'} \leq r_{CB}$ for all a, a'.
- If the interdealer rate difference between two assets is less than the facility rate, the facility will not be used by any dealer: $S_i^{a,a'} = S_i^{a',a} = 0 \; \forall i = 1, ..., N_D$.
- If $r_D^a - r_D^{a'} = r_{CB}$ then q_{dD}^a and $S_d^{a,a'}$ are not separately pinned down. As a result, for the rest of this section we redefine the amount that dealer d obtains of asset a from the central bank q_{dD}^a to include the amount it gets or gives via the facility.

This implies the following are all necessary conditions in equilibrium:

$$\begin{aligned} r_D^a - r_D^{a'} &\leq r_{CB} && \forall a, a' : a \neq a', \\ \min\left\{r^{CB} - (r_D^a - r_D^{a'}), r^{CB} - (r_D^{a'} - r_D^a)\right\} \sum_d q_{dD}^a &= 0 && \forall a, a' : a \neq a', \\ \sum_d \sum_a q_{dD}^a &= 0, \end{aligned}$$

where the final condition follows from the fact that with a swap facility, the total incomings and outgoings to the facility must net out to zero.

In Online Appendix O3, we show that these conditions, together with the first-order conditions in equations 4, 5 and 6, define a unique equilibrium that always exists. The equilibrium conditions are nonlinear, so we solve for the equilibrium numerically.

D.4 Swap facility: constrained

We now consider a constrained swap facility, where the amount dealers can borrow of an asset from the facility is limited by central bank holdings h_{CB}^a. The marginal benefits of the facility and interdealer lending are unchanged, but now dealers can only arbitrage differences across the swap and interdealer markets up to the limits of the facility. As a result:

- The difference between two interdealer rates a and a' can only exceed the facility rate if dealers have obtained as much of the asset with the lower rate as they can.

- As before, if the difference between two interdealer rates is less than the facility rate, it will be unused.
- As before, the amount dealers obtain of an asset via the interdealer market cannot be separated from the amount obtained via the facility, so we redefine the amount that dealer d obtains of asset a from the central bank q^a_{dD} to include the amount it gets or gives via the facility.

The optimality conditions governing the choice between interdealer repo and the swap facility are now:

$$\sum_{d=1}^{N_d} q^a_{dD} \;\geq\; -h^a_{CB} \qquad \forall a, \tag{D3}$$

$$\sum_{a=1}^{N_a}\sum_{d=1}^{N_d} q^a_{dD} \;=\; 0 \tag{D4}$$

$$\big[\bar{r}_D - r^a_D - r_{CB}\big]_+ \big(-\sum_d q^a_{dD} - h^a_{CB}\big) \;=\; 0 \qquad \forall a, \tag{D5}$$

$$\big[r_{CB} - (\bar{r}_D - r^a_D)\big]_+ [-\sum_d q^a_{dD}]_+ \;=\; 0 \qquad \forall a, \tag{D6}$$

$$(\bar{r}_D - r^a_D)\,[\sum_d q^a_{dD}]_+ \;=\; 0 \qquad \forall a, \tag{D7}$$

where we use the shorthand $[z]_+ = \max(z, 0)$, and $\bar{r}_D$ is the highest interdealer rate.

The first condition constrains the amount of asset a that central bank can provide. The second says the assets exchanged via the swap facility must sum to zero. The third says that if a's interdealer rate is more than r_{CB} below the maximum interdealer rate, the central bank's supplies of a must be exhausted. The fourth says that if dealers are acquiring asset a via the facility, the asset's interdealer rate must be at least r_{CB} below the maximum. The fifth says that if an asset is being provided to the central bank by dealers, its interdealer rate must equal the maximum.

In Online Appendix O3, we show that these conditions, together with the first-order conditions in equations 4, 5 and 6, define a unique equilibrium that always exists. The equilibrium conditions are nonlinear, so we solve for the equilibrium numerically.

Appendix: Figures & Tables

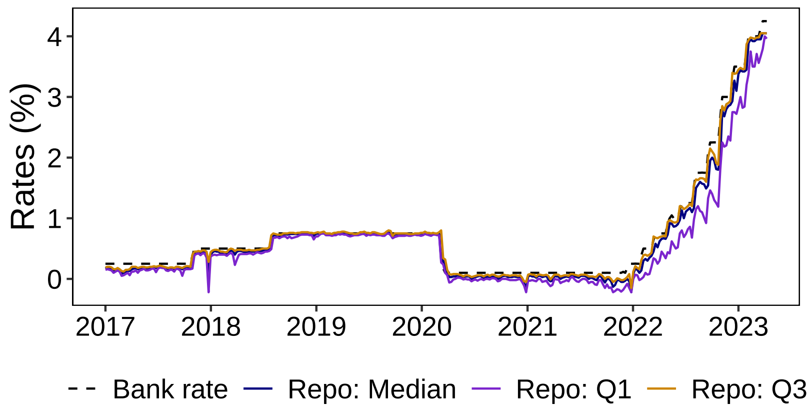


Figure A1: Rates through time on dealer repo lending

Note: Figure show the median, 1st and 3rd quartile of rates that dealers earn on their repo lending (solid lines), vs the central bank policy rate (dashed line)

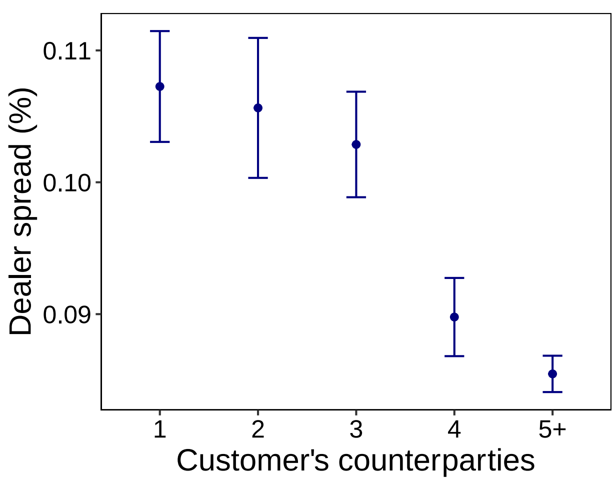


Figure A2: Dealer spreads by number of customer's counterparties

Note: Figure summarizes how the spreads dealers earn on their trading with customers depends on how many counterparties these customers are connected to. We restrict the dataset to trades between dealers and customers. Points show the difference between the rate a dealer earns when lending relative to when borrowing, conditional on the number of counterparties of the client with whom they are trading, after controlling for dealer-asset-date fixed effects. 95% confidence intervals are shown based on standard errors that are two-way clustered by customer and date.

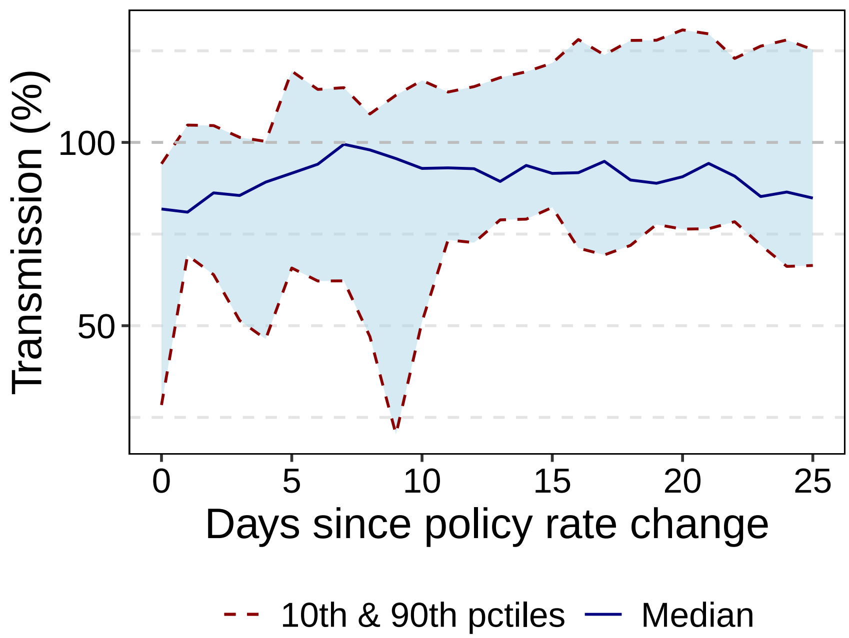


Figure A3: Monetary policy transmission

Note: Figure shows how monetary policy changes are transmitted into average interdealer repo rates. For a given monetary policy shift at time t, and a date $t + \tau$, we compute the change in average interdealer repo rates from $t - 2$ to $t + \tau$ as a percentage of the change in the policy rate over the same period. We then take the median of this across all monetary policy changes for each $\tau = 1, ..., 25$ and plot this as the blue line in each graph. The red dashed lines show the 90th and 10th percentiles over each monetary policy change. To avoid transmission computations being polluted by term repo that incorporates expected rate changes, we compute this based only on overnight and next day repo.

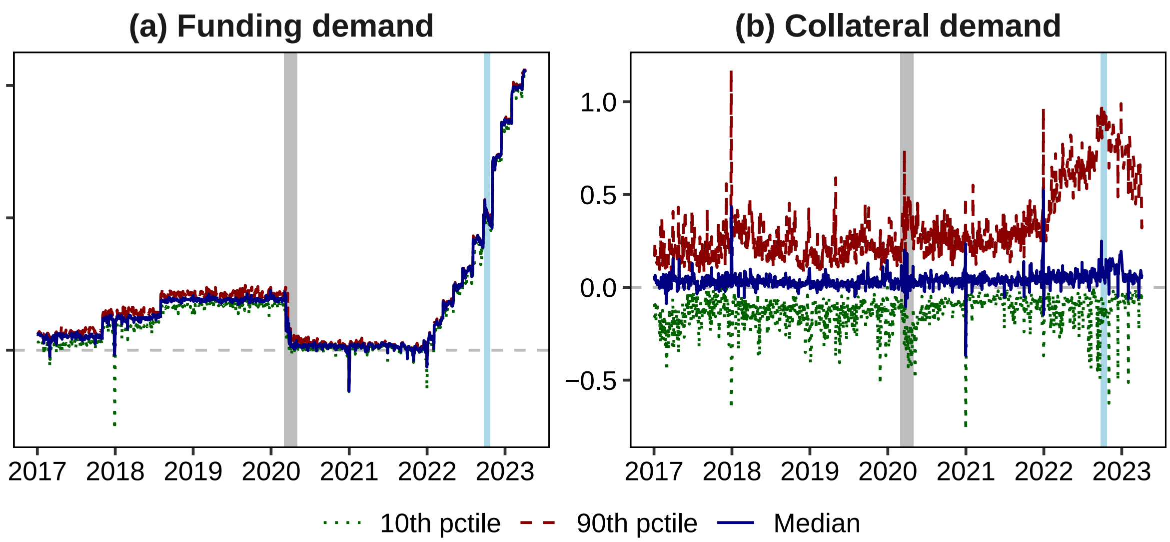
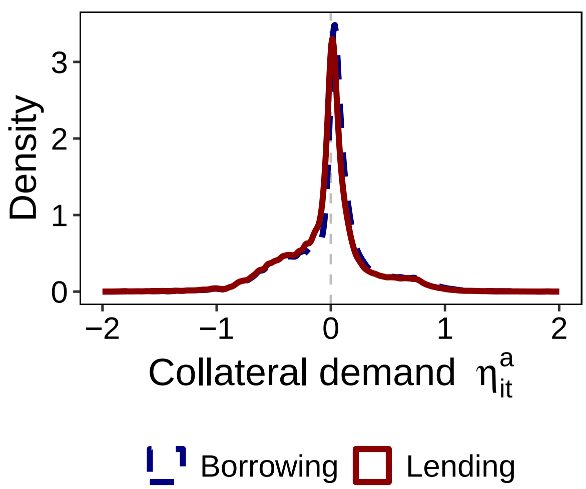
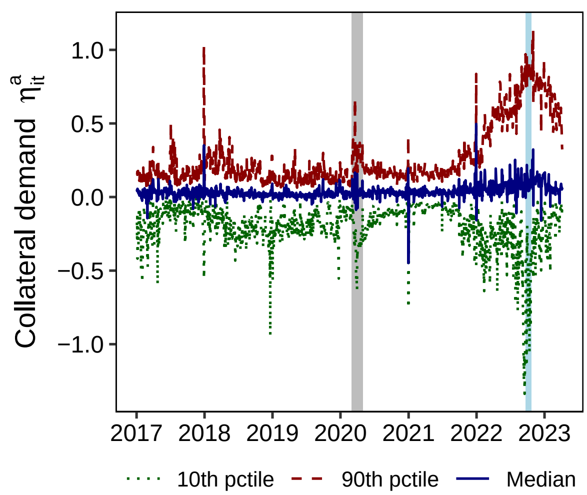


Figure A4: Funding & collateral demand through time: maturity robustness

Note: Figures show the robustness of our estimates of funding and collateral demand when we include only overnight and next day bonds in our estimation.



(a) Collateral demand density



(b) Collateral demand through time

Figure A5: Collateral demand on borrowing vs. lending

Note: Figures summarises the distribution of collateral demand where we allow a firm's collateral demand η_{it}^{a} to differ according to whether it is lending or borrowing. We estimate collateral demand as described in Section C.2. The first panel plots the distribution of our estimates of collateral demand for borrowing and lending. The second panel replicates the second panel of Figure 4 with these new estimates.

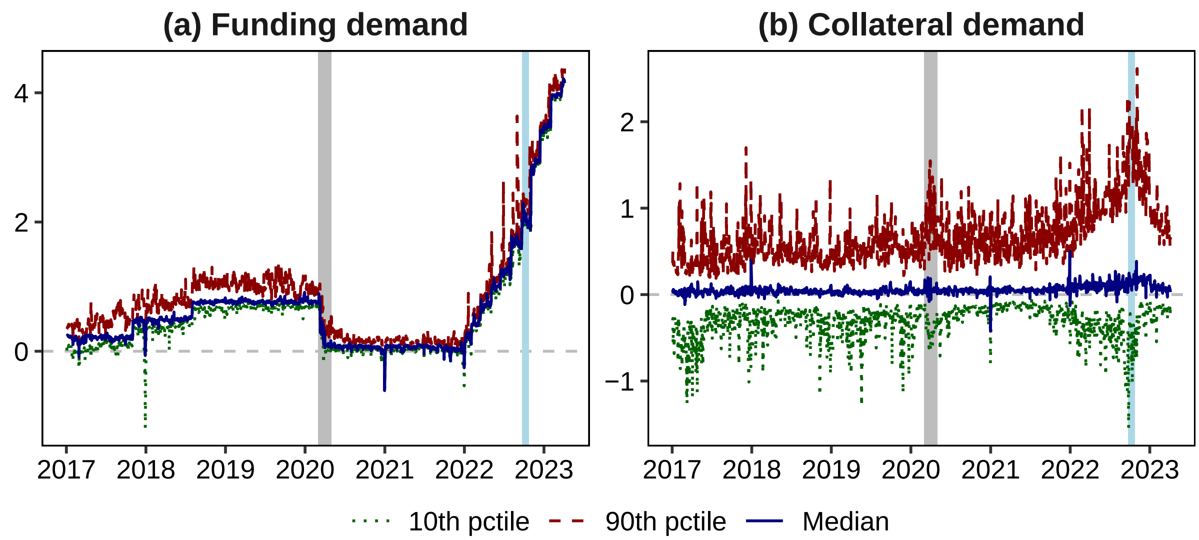


Figure A6: Funding & collateral demand through time: alternative instrument

Note: Figures show the robustness of our estimates of funding and collateral demand to changing the definition of our instrumental variable, as described in Section C.3.

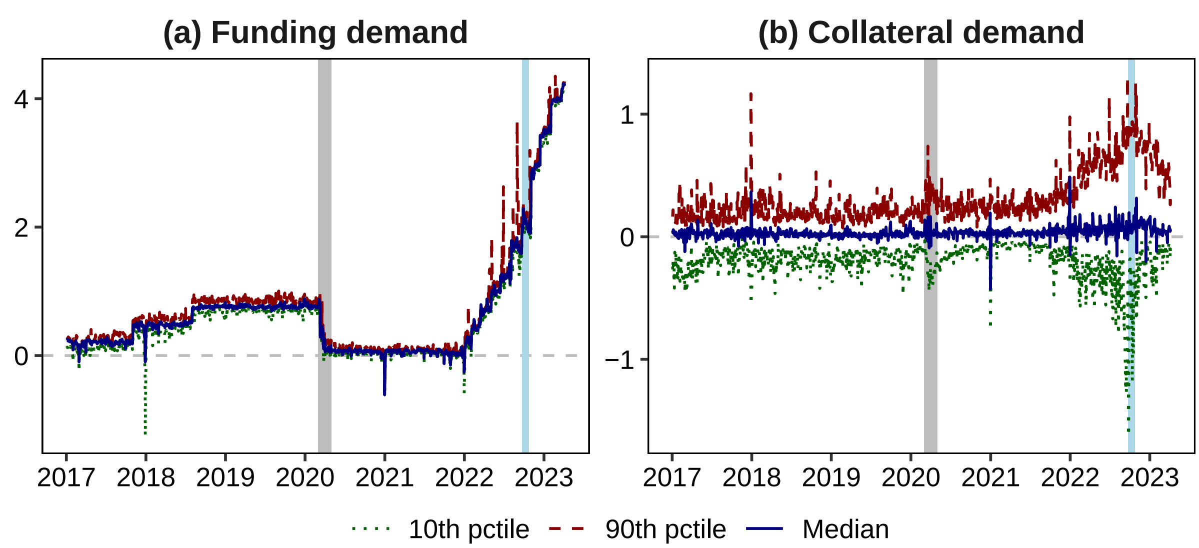


Figure A7: Funding & collateral demand through time: robustness to dropping bonds

Note: Figures show the robustness of our estimates of funding and collateral demand to omitting the ten most traded bonds from our estimation.

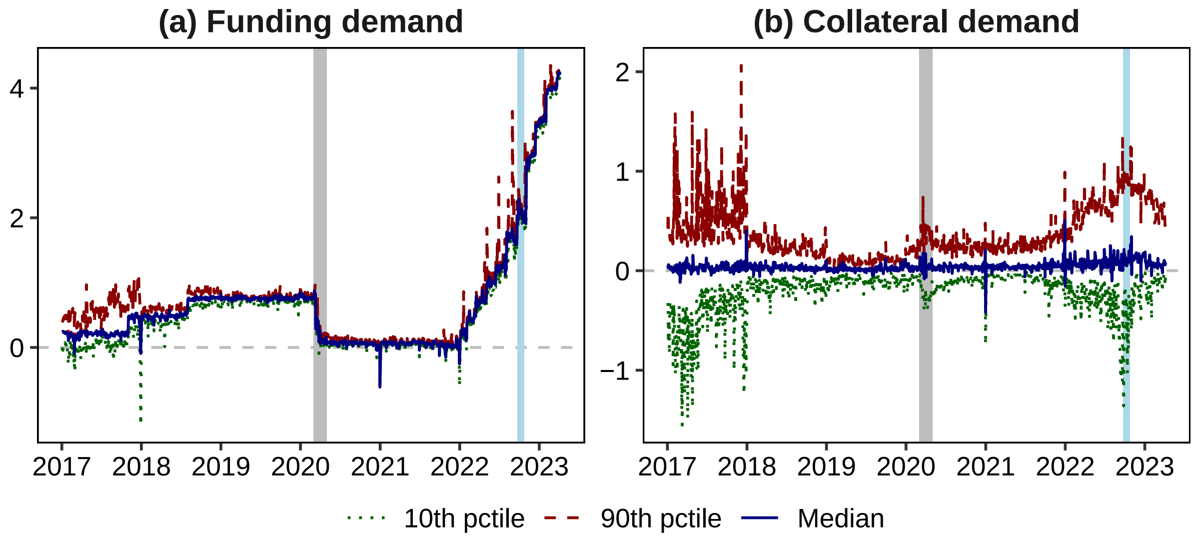


Figure A8: Funding & collateral demand through time: risk robustness

Note: Figures show the robustness of our estimates of funding and collateral demand when we allow our curvature parameters κ and σ^2 to vary by year.

Table A1: Summary Statistics

	Share (%)
Maturity	
1 day	76
of which: overnight repo	39
of which: tomorrow/next day repo	37
of which: other	0
Over 1 day	24
of which: up to 2 weeks	12
of which: 2 weeks plus	11
Clearing	
Cleared	53
Bilateral	46
Segment	
Triparty	0
Dealer-Bank to Dealer-Bank	56
Dealer-Bank to Customer	44

Note: Share shows percentage of total volume in each category. Cleared trades are cleared via a central counterparty. Overnight repos are agreed at date t, the first leg takes place at t, and the second takes place at $t+1$. Next day repos are agreed at date t, the first leg takes place at $t+1$, and the second takes place at $t+2$. Trades with central counterparties are counted as a single trade between two end users rather than two offsetting trades with the central counterparty. Dealer-banks include both dealers and banks.

Table A2: Summary Statistics: bonds

	Mean	Median	Std dev.	10^{th} pctile	90^{th} pctile
Volumes					
Amount issued (£bn)	21.3	20.6	10.2	8.1	35.3
Central bank purchases (£bn)	6.4	3.6	7.7	0.0	19.0
Share purchased (%)	21.7	14.7	22.8	0.0	55.8
Bond float (£bn)	14.7	14.2	5.5	7.7	22.3
Repo trading volume (£bn)	1.2	0.9	1.2	0.3	2.6
Prices					
Repo rate (%)	0.7	0.4	0.9	0.0	1.8
Spread over base rate (bps)	-8.4	-4.8	15.3	-19.8	1.5

Note: Table summarizes the features of the bonds in our sample. For each bond-date pair in our sample, we record (a) the amount of the bond in issuance, (b) the net amount purchased by the central bank of that purchase up to that date, (c) the share of the amount in issue held by the central bank, (d) the amount in issue minus the amount held by the central bank, (e) the trading volume, (f) the average repo rate, and (g) the average repo rate expressed as a spread over the base rate. We summarize the distribution of each of these variables across all dates and bonds.

Table A3: Trading activity by sector

	Trade Share (%)	Daily net lending (%)	Daily net lending (£bn)
Dealer	66.2	-3.7	-4.6
Bank	11.7	-31.0	-7.4
Hedge Fund	10.3	0.7	-0.3
Fund	4.2	62.7	5.1
MMF	2.9	97.6	6.2
PFLDI	2.8	18.4	0.8
Other	1.9	0.5	0.4

Note: Table summarises the behaviour of different sectors. The first numeric column shows the volume-weighted trade shares of each sector. The second and third numeric columns summarise the average daily net lending of each sector, in % and £bn respectively. The net lending figures only include days when a given sector traded at least once. For computing trade shares and net lending trades with central counterparties are counted as a single trade between two end users rather than two offsetting trades with the central counterparty.

Table A4: Dealer rates on borrowing & lending

	Repo rate (%)		
	(1)	(2)	(3)
Dealer lending	0.155***	0.148***	0.088***
	(0.019)	(0.012)	(0.008)
R^2	0.25	0.40	0.87
Observations	996,700	996,155	726,981
Mean dep. var.	-0.087	-0.087	-0.087
Std. dev. dep. var.	0.153	0.153	0.153
Date fixed effects	Yes		
Date-Dealer fixed effects		Yes	
Date-Dealer-Asset fixed effects			Yes

Note: Table shows how the rates dealers charge on their repo lending exceed those they pay on their borrowing. The table shows regressions of repo rates (net of the central bank base rate) on a dummy for whether a dealer is lending in that transaction along with a set of fixed effects, where the sample includes only dealer-client trades and dealers lending is the excluded category. Transactions with CCPs, governments and central banks are excluded here. Standard errors are clustered at the level of the fixed effect. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table A5: Rate variation

Fixed effects	R-squared
Deal characteristics	
Date	0.33
Date-Asset	0.82
Date-Maturity	0.47
Date-Asset-Maturity	0.94
Trader characteristics	
Date-Borrower	0.52
Date-Lender	0.43
Date-Borrower-Lender	0.63

Note: Table shows the R-squared of a regression of repo rates (net of the central bank base rate) on the fixed effects shown in each row. Date-Asset means that fixed effects with the interaction of the gilt provided as collateral and the date of the transaction are included as regressors.

Table A6: Network: Summary Statistics

	Mean	Median	10th pctile	90th pctile	Std. Dev.
Number of trading counterparties					
Bank	15	3	1	18	45
Fund	3	2	1	7	3
Dealer	205	166	74	383	128
Hedge Fund	4	2	1	12	5
MMF	4	4	1	8	3
Other	3	2	1	6	3
PFLDI	6	5	1	9	3
Share of top trading counterparty (%)					
Bank	70	71	34	100	27
Fund	78	86	45	100	23
Dealer	23	18	10	35	18
Hedge Fund	73	82	31	100	28
MMF	71	77	34	100	29
Other	80	100	40	100	25
PFLDI	58	53	30	100	24

Note: Table shows summary statistics on the network structure. For each firm we count the number of counterparties with which they trade across the whole sample period, and then summarize this for each sector in the first part of the table. In the second half of the table, for each firm we compute the amount it trades in aggregate with its most common counterparty, as a percentage of all its trading, across the whole sample period, and summarize its distribution across sectors. We exclude central counterparties from these calculations.

Table A7: Network Persistence: Summary Statistics

	New links (%)	Disappearing links (%)
By year		
Unweighted	33	33
Trade-weighted	5	4
By month		
Unweighted	31	28
Trade-weighted	10	7

Note: Table shows the persistence of the network through time. For each year, we count the number of unique links between counterparties, before computing the percentage of these that are new relative to the previous year, and the percentage of these that are not present the following year. We average these and display the results in the first row. The second repeats this computation, but weights by trading volumes, such that *new links* measures the percentage of trading volume in a year that is on links not present the previous year, and *disappearing links* measures the percentage of trading volume in a year taking place on links not present the following year. The final two rows repeat these computations at the monthly frequency. We exclude central counterparties from these calculations.

Table A8: Repo rates & collateralisation type

	Repo rate (%)				
	(1)	(2)	(3)	(4)	(5)
General Collateral	0.09***	0.09***	0.09***	0.09***	0.09***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
R^2	0.34	0.16	0.52	0.43	0.47
Observations	6,080,322	6,079,453	6,038,193	6,035,545	6,079,468
Mean dep. var.	-0.13	-0.13	-0.13	-0.13	-0.13
Std. dev. dep. var.	0.12	0.12	0.12	0.12	0.12
Date fixed effects	Yes	No	No	No	No
Borrower-Lender fixed effects	No	Yes	No	No	No
Borrower-Date fixed effects	No	No	Yes	No	No
Lender-Date fixed effects	No	No	No	Yes	No
Maturity-Date fixed effects	No	No	No	No	Yes

Note: Table shows how repo rates vary according to whether collateral is exchanged via 'Delivery by Value' – denoted general collateral – or otherwise. The table shows the results of regressions of rates (net of central bank base rate) on a dummy for whether the transaction involved general collateral and the listed fixed effects. Standard errors are clustered at the level of the fixed effect. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table A9: Identifying variation: rates & quantities

	Variables	% variation explained
Funding demand ν_{it}		
Within i, across t	r^0_{it}	91
Within i, across t	$Q_{it} + \sum_m q^0_{imt}$	1
Within t, across i	r^0_{it}	2
Within t, across i	$Q_{it} + \sum_m q^0_{imt}$	88
Collateral demand η^a_{it}		
Within ia, across t	$r^0_{it} - r^a_{it}$	35
Within ia, across t	$\sum_m (q^0_{imt} - q^a_{imt})$	62
Within it, across a	$r^0_{it} - r^a_{it}$	87
Within it, across a	$\sum_m (q^0_{imt} - q^a_{imt})$	13
Within at, across i	$r^0_{it} - r^a_{it}$	7
Within at, across i	$\sum_m (q^0_{imt} - q^a_{imt})$	88

Note: Table shows the variation in the repo rates and quantities that pins down cross-sectional and time series variation in funding and collateral demand. In the first row, we regress our estimated values of ν_{it} on firm i's general collateral repo rate at time t r^0_{it} (for firms that trade against general collateral at time t), along with firm fixed effects. The third column shows the within-R squared from this regression, capturing the variation in across firm-within time funding demands that is explained by r^0_{it}. Subsequent rows repeat this for different fixed effects and explanatory variables, and collateral demand rather than funding demand.

Table A10: Estimating Collateral Demand: Model vs Reduced Form

	Firm collateral demand η^a_{it}	
	(1)	(2)
Asset repo - GC repo rate	1.1***	
	(0.002)	
Firm asset repo - GC repo rate		0.95***
		(0.001)
R^2	0.14	0.20
Observations	2,642,311	2,642,311

Note: Table summarises the relationship between our structural estimates of collateral demand η^a_{it} and reduced-form estimates based solely on repo rates. The first column regresses η^a_{it} on the difference betwen the general collateral repo rate r^0_{it} averaged across firms at time t and the repo rate for asset a averaged across firms at time t. The second column regresses η^a_{it} on the difference betwen firm i's general collateral repo rate r^0_{it} at time t and its repo rate for asset a at time t. Standard errors are iid. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table A11: Parameter estimates: Robustness

	Repo rate r^a_{ijt} (%)				
	Baseline	Overnight	Directed demand	Equal weights	Omit 10 bonds
	(1)	(2)	(3)	(4)	(5)
$\sum_l q^l_{ijt}$	-0.02**	-0.002	-0.01**	0.02	-0.02**
	(0.008)	(0.006)	(0.007)	(0.04)	(0.008)
q^a_{ijt}	-0.18***	-0.18***	-0.08**	-0.58	-0.19***
	(0.02)	(0.05)	(0.03)	(0.42)	(0.04)
Wald (1st stage), $\sum_l q^l_{ijt}$	96.2	59.6	101.6	101.9	102.1
Wald (1st stage), q^a_{ijt}	15.9	21.1	30.5	8.29	32.5
Observations	815,665	343,986	815,665	403,648	637,638
Firm-asset-date fixed effects	Yes	Yes	No	Yes	Yes
Firm-counterparty fixed effects	Yes	Yes	Yes	Yes	Yes
Firm-asset-date-dir. fixed effects	No	No	Yes	No	No

Note: Table shows the results of estimating Equation 10 via two-stage least squares under our various robustness tests. The first column shows our baseline results, as in Table 4. The second shows results when we restrict our estimation to only include overnight and next day repos. The third shows results when we allow collateral demand to vary according to whether it is incoming or outgoing for a firm. The fourth shows results when we amend our instrument to place equal weights on each bond a firm has traded. The fifth shows results when we omit the ten most frequently traded bonds in our sample. Standard errors are three-way clustered by firm-counterparty pair, asset, and date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table A12: Funding demand by sector: robustness

	Funding demand ν_{it}					
	Baseline	Overnight	Directed demand	Equal weights	Omit 10 bonds	Het. risk
	(1)	(2)	(3)	(4)	(5)	(6)
Bank	0.01***	0.0008	0.009***	-0.02***	0.010***	0.002*
	(0.0008)	(0.0007)	(0.0007)	(0.001)	(0.0008)	(0.001)
Dealer	0.12***	0.11***	0.06***	0.35***	0.13***	0.13***
	(0.002)	(0.001)	(0.0008)	(0.004)	(0.002)	(0.002)
Fund	-0.01***	-0.02***	-0.009***	-0.02***	-0.01***	-0.02***
	(0.0006)	(0.0008)	(0.0005)	(0.001)	(0.0007)	(0.0010)
Hedge Fund	0.008***	0.010***	0.002***	0.02***	0.01***	0.004***
	(0.0008)	(0.0007)	(0.0007)	(0.001)	(0.0008)	(0.0009)
MMF	-0.07***	-0.05***	-0.04***	-0.09***	-0.07***	-0.08***
	(0.001)	(0.001)	(0.0010)	(0.003)	(0.001)	(0.002)
PFLDI	-0.004***	-0.03***	0.0003	-0.02***	-0.003**	-0.01***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)
R^2	0.98	0.97	0.99	0.85	0.97	0.94
Observations	203,000	119,698	203,000	203,001	192,256	203,000
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: Table shows our estimates of funding demand ν_{it} vary under various robustness tests. The first column shows our baseline results, as in Table 6. The second shows results when we restrict our estimation to only include overnight and next day repos. The third shows results when we allow collateral demand to vary according to whether it is incoming or outgoing for a firm. The fourth shows results when we amend our instrument to place equal weights on each bond a firm has traded. The fifth shows results when we omit the ten most frequently traded bonds in our sample. The sixth shows results when we allow our curvature parameters κ and σ^2 to vary by year. Standard errors are clustered by date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Table A13: Collateral demand by sector: robustness

	Collateral demand η^a_{it}					
	Baseline	Overnight	Directed demand	Equal weights	Omit 10 bonds	Het. risk
	(1)	(2)	(3)	(4)	(5)	(6)
Bank	-0.0004	-0.02***	0.003***	-0.002	-0.0007	-0.02***
	(0.0010)	(0.001)	(0.0009)	(0.001)	(0.001)	(0.001)
Dealer	0.13***	0.10***	0.06***	0.41***	0.14***	0.14***
	(0.001)	(0.001)	(0.0009)	(0.002)	(0.001)	(0.001)
Fund	-0.04***	-0.06***	-0.04***	-0.04***	-0.05***	-0.05***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Hedge Fund	0.03***	-0.0007	0.02***	0.06***	0.02***	0.03***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
MMF	-0.03***	-0.06***	-0.04***	0.03***	-0.01***	-0.03***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
PFLDI	-0.19***	-0.18***	-0.17***	-0.28***	-0.19***	-0.20***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
R^2	0.11	0.12	0.13	0.08	0.11	0.08
Observations	2,504,327	1,926,753	2,778,187	2,504,358	2,088,889	2,504,327
Date fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: Table shows our estimates of collateral demand η^a_{it} vary under various robustness tests. The first column shows our baseline results, as in Table 6. The second shows results when we restrict our estimation to only include overnight and next day repos. The third shows results when we allow collateral demand to vary according to whether it is incoming or outgoing for a firm. The fourth shows results when we amend our instrument to place equal weights on each bond a firm has traded. The fifth shows results when we omit the ten most frequently traded bonds in our sample. The sixth shows results when we allow our curvature parameters κ and σ^2 to vary by year. Standard errors are clustered by asset-date. ***, ** and * respectively denote significance at the 0.1%, 1% and 5% levels of significance.

Online Appendix: Additional Proofs

O1 Baseline Model

In this section we solve for the equilibrium and show that it exists and is unique. We proceed in three steps. First, we set out the relevant equilibrium conditions in quantities having substituted out endogenous rates. Second, it is convenient for our proof of uniqueness to define a quadratic programme whose Karush-Kuhn-Tucker (KKT) conditions coincide with the model's equilibrium conditions. We solve this problem, which is equivalent to solving the model. Third, we show existence and uniqueness by using standard results from quadratic programming.

O1.1 Equilibrium conditions

We combine first order conditions to eliminate equilibrium repo rates and leave only a system of linear equations in trading quantities.

For dealer to customer trade, we substitute out r^a_{dc} by combining the dealer's and customer's first order conditions in Equations 4 and 5, to obtain the following set of equations, one for each dealer to customer trade:

$$\nu_d - \eta^a_d - \epsilon^a_{dc} - \kappa Q_d - \kappa\sigma^2 Q^a_d - \kappa \sum_{\ell\in\mathcal{A}} q^\ell_{dc} - \kappa\sigma^2 q^a_{dc} = \nu_c - \eta^a_c - \epsilon^a_{cd} - \kappa Q_c - \kappa\sigma^2 Q^a_c. \tag{O1}$$

For interdealer trade, we first take the mean of each dealer's first order condition with respect to the interdealer market, Equation 6. Given that there is a single interdealer rate for each asset, this averaging expresses this interdealer rate as a function of dealer's mean preferences and net positions: $r^a_D = \bar{\nu} - \kappa\bar{Q} - \bar{\eta}^a - \kappa\sigma^2\bar{Q}^a - \bar{\epsilon}^a_D$, where $\bar{x} \equiv \frac{1}{N_d}\sum_{d\in\mathcal{D}} x_d$, N_d is the number of dealers and $\mathcal{D}$ is the set of dealers. Substituting this expression into a dealer's first order condition, we get the following set of equilibrium conditions:

$$\nu_d - \eta^a_d - \epsilon^a_{dD} - \kappa Q_d - \kappa\sigma^2 Q^a_d = \bar{\nu} - \bar{\eta}^a - \bar{\epsilon}^a_D - \kappa\bar{Q} - \kappa\sigma^2\bar{Q}^a. \tag{O2}$$

There is one such equation for each asset and each dealer. For each asset, however, one dealer's first order condition is redundant given the averaging. The remaining equilibrium condition comes from dealer market clearing Equation 7, which we repeat for convenience:

$$\sum_d q^a_{dD} = 0. \tag{O3}$$

Given that Q and $\bar{Q}$ are just linear functions of individual q, collectively these three sets of Equations O1, O2 and O3 give a linear system in these q. There are as many equations as unknowns: for each dealer-customer-asset combination we have an equilibrium condition like O1, and collectively O2 and O3 give as many conditions as there are dealer-asset combinations.

O1.2 Solution

To invert this linear system of equations, it is convenient to work with a quadratic programme that delivers the same equilibrium conditions. Let $\mathcal{L} \equiv \{(d,c,a) : G^a(d,c) = 1\}$ be the set of feasible firm to firm links. Consider the following quadratic programme, where as a reminder we use indices d and c to denote dealers and customers, respectively, and i to denote firms of any type:

$$\min_{\{q^a_{dc}\}_{(d,c,a)\in\mathcal{L}},\,\{q^a_{dD}\}} \quad \Phi\big(\{q^a_{dc}\},\{q^a_{dD}\}\big) \quad \text{subject to} \quad \sum_{d=1}^{N_d} q^a_{dD} = 0 \;\; \text{for each } a \in \mathcal{A}, \tag{O4}$$

where

$$\Phi = \frac{\kappa}{2}\sum_i (Q_i)^2 \;+\; \frac{\kappa\sigma^2}{2}\sum_{i,a}(Q^a_i)^2 \;+\; \frac{\kappa}{2}\sum_{(d,c)}\big(\sum_{\ell\in\mathcal{A}} q^\ell_{dc}\big)^2 \;+\; \frac{\kappa\sigma^2}{2}\sum_{(d,c,a)}(q^a_{dc})^2$$
$$-\sum_i \nu_i Q_i + \sum_{i,a}\eta^a_i Q^a_i + \sum_{(d,c,a)\in\mathcal{L}}(\epsilon^a_{dc} - \epsilon^a_{cd})q^a_{dc} + \sum_{d,a}\epsilon^a_{dD}q^a_{dD}. \tag{O5}$$

Now consider the Lagrangian associated with this problem:

$$\mathcal{L}\big(\{q^a_{ij}\},\{q^a_{iD}\},\{\lambda^a\}\big) \;=\; \Phi\big(\{q^a_{ij}\},\{q^a_{iD}\}\big) \;+\; \sum_{a\in\mathcal{A}}\lambda^a\left(\sum_{i=1}^{N_d} q^a_{iD}\right).$$

where λ^a is the Lagrange multiplier on market clearing for asset a. We take the first-order condition with respect to q^a_{ij}, noting that q^a_{ij} enters Q_i and Q^a_i positively and Q_j and Q^a_j

negatively. This yields the following expression, which is equivalent to Equation O1:

$$\kappa\big(Q_d - Q_c\big) + \kappa\sigma^2\big(Q_d^a - Q_c^a\big) + \kappa\sum_{\ell\in\mathcal{A}} q_{dc}^{\ell} + \kappa\sigma^2 q_{dc}^a - (\nu_d - \nu_c) + (\eta_d^a - \eta_c^a) + (\epsilon_{dc}^a - \epsilon_{cd}^a) = 0.$$

For q_{dD}^a we obtain the first-order condition:

$$\kappa Q_d + \kappa\sigma^2 Q_d^a - \nu_d + \eta_d^a + \epsilon_{dD}^a + \lambda^a = 0.$$

By comparing this to the dealer's interdealer first order condition Equation 6, it is immediately obvious that $\lambda^a = r_D^a$: both of these vary only across assets, and all other parts of the equation are the same. This first order condition to the quadratic programme is thus equivalent to the dealer's first order condition. Finally, the equality constraint is simply interdealer market clearing. The equations that define the model's decentralized equilibrium are thus identical to the equations that solve the Lagrangian problem here. It follows that if this Lagrangian has a unique solution, then the decentralized outcome must have the same unique solution.

Solving this linear system is then just a question of stacking them correctly and then inverting, which requires some notation. Let firms be ordered $i = 1, ..., N_f$, with dealers first. Let $\boldsymbol{q^a}$ stack firms' trades in asset a, with interdealer trades coming before dealer-customer trades. If there are N_d dealers trading this asset, that means the first element of $\boldsymbol{q^a}$ is the first dealer's borrowing on the interdealer market, whilst the $(N_d + 1)$'th element is the first dealer's borrowing from the first customer. Let $\boldsymbol{q}$ be the length N vector that stacks $\boldsymbol{q^a}$ in order $a = 1, ..., N_a$.

Define the following matrices that map $\boldsymbol{q}$ into the sums that define firms' utility. Let $\boldsymbol{M_F}$ be the matrix such that $\boldsymbol{M_F q}$ contains Q_k for each firm k, taking into account the set of firms to which it is connected.[43] Let $\boldsymbol{M_{FA}}$ be the matrix such that $\boldsymbol{M_{FA} q}$ is a vector of Q_k^a for the relevant firm k and asset a. Let $\boldsymbol{M_{FF}}$ be the matrix such that $\boldsymbol{M_{FF} q}$ gives $\sum_{\ell\in\mathcal{A}} q_{dc}^{\ell}$ for each dealer-customer pair. Finally, let $\boldsymbol{M_I}$ be the matrix such that $\boldsymbol{M_I q}$ gives q_{dc}^a for each dealer-customer pair and zero otherwise.

Stack all trades across assets as $\boldsymbol{q}$, and collect the interdealer clearing constraints as $C\boldsymbol{q} = 0$, where C has one row per asset with ones on the interdealer positions and zeros

[43] For each dealer, this matrix will contain ones for any entry in q such that the dealer is a counterparty. For each customer, it will contain *minus* ones for any entry in q such that the customer is a counterparty.

elsewhere. We collect the primitives as follows:

$$\alpha_d^a = \nu_d - \eta_d^a - \epsilon_{dD}^a, \qquad \tilde{\alpha}^{\,a} = \alpha^a - \tfrac{1}{N_d}\sum_d \alpha_d^a,$$

$$\delta_{dc}^a = (\nu_d - \eta_d^a - \epsilon_{dc}^a) - (\nu_c - \eta_c^a - \epsilon_{cd}^a), \qquad \Delta_c^a = \sum_{d:(d,c)\in\mathcal{L}_a} \delta_{dc}^a,$$

We then define $\tilde{\alpha}$ and Δ as the corresponding stacked vectors. These linear terms can then be collected as:

$$\boldsymbol{b} \;=\; \boldsymbol{S}_D^\top \tilde{\alpha} \;+\; \boldsymbol{L}^\top \Delta,$$

where $\boldsymbol{S}_D$ selects the interdealer positions so that each block receives $\tilde{\alpha}^{\,a}$, and $\boldsymbol{L}$ aggregates the dealer-customer rows so that each customer c in asset a receives the primitive sum Δ_c^a. The quadratic part of the objective defines the Hessian:

$$\boldsymbol{H} = \kappa\, \boldsymbol{M}_F^\top \boldsymbol{M}_F + \kappa\sigma^2\, \boldsymbol{M}_{FA}^\top \boldsymbol{M}_{FA} + \kappa\, \boldsymbol{M}_{FF}^\top \boldsymbol{M}_{FF} + \kappa\sigma^2\, \boldsymbol{M}_I^\top \boldsymbol{M}_I. \tag{O6}$$

The KKT system for the quadratic programme (O4)-(O5) in compact matrix form is therefore:

$$\begin{bmatrix} \boldsymbol{H} & C^\top \\ C & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{q} \\ \lambda \end{bmatrix} = \frac{1}{K} \begin{bmatrix} \boldsymbol{b} \\ 0 \end{bmatrix}, \tag{O7}$$

where $\lambda = (\lambda^a)_a$ are the multipliers on the interdealer clearing constraints, $K = \kappa(1+\sigma^2)$, and the system is solved by simple linear inversion.

O1.3 Existence and uniqueness

Existence and uniqueness require that the left-hand KKT matrix in Equation O7 be non-singular. Boyd and Vandenberghe (2004) state that in our case this requires that the Hessian $\boldsymbol{H}$ be positive definite on the nullspace of C.

$\boldsymbol{H}$ consists of inner product terms that are positive semi-definite by construction, and so $\boldsymbol{H}$ itself is positive semi-definite. $\boldsymbol{H}$ is positive definite on the feasible subspace defined by the interdealer market clearing constraint if, for any feasible, non-zero $\boldsymbol{\Delta}q$:

$$\boldsymbol{\Delta q}^\top \boldsymbol{H} \boldsymbol{\Delta q} \equiv \kappa \|\boldsymbol{M_F \Delta q}\|^2 + \kappa\sigma^2 \|\boldsymbol{M_{FA} \Delta q}\|^2 + \kappa \|\boldsymbol{M_{FF} \Delta q}\|^2 + \kappa\sigma^2 \|\boldsymbol{M_I \Delta q}\|^2 > 0, \tag{O8}$$

This holds by definition of the matrices $\boldsymbol{M_I}$ and $\boldsymbol{M_{FA}}$, provided that the curvature parameters σ^2 and κ are strictly positive. If $\mathbf{\Delta}q$ is non-zero for any dealer-customer pair, the last term is strictly positive. Otherwise, it must be that some dealer-asset quantity Q_k^a is non-zero, so the second term is strictly positive. Intuitively, the only potential flat directions correspond to common shifts of all dealers' positions within an asset, which leave all squared terms unchanged. However, such shifts necessarily violate the interdealer market-clearing constraints unless they are zero.

It follows that the block matrix in Equation O7 is nonsingular, and the system has a unique solution. This solution coincides with the unique decentralized equilibrium of the model.

O2 Model with Reverse Repo Facility

Here we prove that a unique equilibrium exists in the model with a central bank reverse repo facility. We prove this for the case with constraints on how much the facility can provide of each asset, leaving the unconstrained facility as a special case where these constraints go to infinity. The proof follows the same form as in the baseline model, with a richer set of constraints.

Consider the quadratic programme:

$$\min_{\{q_{dc}^a\}_{(d,c,a)\in\mathcal{L}},\, \{q_{dD}^a\}} \quad \Phi\big(\{q_{dc}^a\}, \{q_{dD}^a\}\big) + \sum_a r_{CB}^a \sum_d q_{dD}^a \text{ s.t. } -h_{CB}^a \le \sum_{d=1}^{N_d} q_{dD}^a \le 0 \ \ \forall a \in \mathcal{A},$$

where h_{CB}^a is the central bank's holdings of asset a, and Φ is defined in Equation O5. The constraint states that dealers in aggregate can lend up to h_{CB}^a of cash to the central bank against asset a.

Let $\mu^a \ge 0$ be the multiplier on $\sum_d q_{dD}^a \le 0$ and $\delta^a \ge 0$ the multiplier on $-h_{CB}^a - \sum_d q_{dD}^a \le 0$. The Lagrangian is:

$$\mathcal{L}(z, \mu, \nu) = \Phi(z) + \sum_a r_{CB}^a \sum_d q_{dD}^a + \sum_a \mu^a \Big(\sum_d q_{dD}^a \Big) + \sum_a \delta^a \Big(-h_{CB}^a - \sum_d q_{dD}^a \Big).$$

The first-order conditions for customer-dealer quantities are the same as in the baseline. The first-order condition for interdealer trade is now:

$$\frac{\partial \mathcal{L}}{\partial q_{dD}^a} = \frac{\partial \Phi}{\partial q_{dD}^a} + r_{CB}^a + \mu^a - \delta^a = 0,$$

and the remaining KKT conditions (per a) are:

$$-h^a_{CB} \leq \sum_d q^a_{dD} \leq 0, \qquad \mu^a \geq 0,\ \delta^a \geq 0, \qquad \mu^a\Big(\sum_d q^a_{dD}\Big) = 0,\ \ \delta^a\Big(h^a_{CB} + \sum_d q^a_{dD}\Big) = 0.$$

We select a convenient representation of admissible multipliers such that the KKT system corresponds to our model's equilibrium conditions. Let the Lagrange multipliers be defined as follows:

$$\mu_a = [r^a_D - r^a_{CB}]_+, \quad \delta_a = [r^a_{CB} - r^a_D]_+$$

where $[z]_+$ is shorthand for $\max(z, 0)$, which is weakly positive by construction.

Substituting these into the first-order condition for interdealer trade gives:

$$\nu_i - \kappa Q_i - \eta^a_i - \kappa\sigma^2 Q^a_i - \epsilon^a_{iD} - r^a_D \ = \ 0,$$

which is identical to the dealer's first-order condition in the model. The complementary slackness conditions become:

$$\Big(\sum_d q^a_{dD}\Big)[r^a_D - r^a_{CB}]_+ = 0, \quad \Big(h^a_{CB} + \sum_d q^a_{dD}\Big)[r^a_{CB} - r^a_D]_+ = 0. \tag{O9}$$

These are equivalent to the equilibrium conditions in equation D2 in Section D.2:

- If $-h^a_{CB} < \sum_d q^a_{dD} < 0$, then $r^a_D = r^a_{CB}$.
- If $\sum_d q^a_{dD} = 0$ then $r^a_D \geq r^a_{CB}$.
- If $\sum_d q^a_{dD} = -h^a_{CB}$, then $r^a_D \leq r^a_{CB}$.

Given the constraints to this quadratic programme are the same as the the constraint on usage of the facility in Section D.2, it's clear that the conditions here are equivalent to the equilibrium conditions in Section D.2, in the sense that if there is a unique solution to this quadratic programme there is also a unique solution to the model.

The proof from here is identical to that in Section O1. The quadratic form of the programme's objective function ensures a minimum exists. The Hessian is exactly as in equation O6, so is positive semi-definite. The feasible set is a closed, convex, non-empty set. By the same arguments as in the previous section, the Hessian is also positive definite if κ and σ are strictly positive. As a result, the solution to this programme exists and is unique, and so the equilibrium of the model with a reverse repo facility exists and is unique.

O3 Model with Swap Facility

Here we prove that a unique equilibrium exists in the model with a central bank swap facility. We prove this for the case with constraints on how much the facility can provide of each asset, leaving the unconstrained facility as a special case where these constraints go to infinity. The proof follows the same form as in the baseline model, with a richer set of constraints.

For each asset $a \in \mathcal{A}$, let:

$$S^a \;\equiv\; -\sum_{d=1}^{N_d} q^a_{dD}$$

denote the central bank's net supply of a to dealers. Let $s^a_+ \geq 0$ be the central bank's outgoings of asset a via the facility. Let $s^a_- \geq 0$ be the central bank's incomings of asset a. At most only one of these can be positive per asset a. By construction:

$$S^a \;=\; s^a_+ - s^a_-, \qquad \sum_{a\in\mathcal{A}} s^a_+ \;=\; \sum_{a\in\mathcal{A}} s^a_-,$$

where the latter equality is the constraint that the swap facility must in aggregate have equal incomings and outgoings. The feasibility restriction states $s^a_+ \leq h^a_{CB}$. There is no cap on s^a_-.

Consider the quadratic programme:

$$\min_{\{q^a_{dc}\},\{q^a_{dD}\},\{s^a_+,s^a_-\}} \quad \Phi\big(\{q^a_{dc}\},\{q^a_{dD}\}\big) \;+\; r_{CB}\sum_{a\in\mathcal{A}} s^a_+ \quad \text{such that}$$

$$S^a - s^a_+ + s^a_- = 0 \quad \forall a, \qquad 0 \leq s^a_+ \leq h^a_{CB} \quad \forall a, \qquad s^a_- \geq 0 \quad \forall a, \qquad \sum_a s^a_+ = \sum_a s^a_-.$$

As above, we select a convenient set of admissible multipliers such that the KKT system is equivalent to our model's equilibrium conditions. Define the multipliers:

$$\xi^a \in \mathbb{R} \;\text{ on }\; S^a - s^a_+ + s^a_- = 0, \qquad \zeta \in \mathbb{R} \;\text{ on }\; \sum_a s^a_+ - \sum_a s^a_- = 0,$$

$$\mu^a \geq 0 \text{ on } s_+^a - h_{CB}^a \leq 0, \qquad \gamma^a \geq 0 \text{ on } -s_+^a \leq 0, \qquad \delta^a \geq 0 \text{ on } -s_-^a \leq 0.$$

Define the Lagrangian:

$$\begin{aligned}\mathcal{L} = \; \Phi \; + \; r_{CB} \sum_a s_+^a + \sum_a \xi^a \left(S^a - s_+^a + s_-^a\right) + \zeta \Big(\sum_a s_+^a - \sum_a s_-^a \Big) \\ + \sum_a \mu^a (s_+^a - h_{CB}^a) - \sum_a \gamma^a s_+^a - \sum_a \delta^a s_-^a. \end{aligned} \tag{O10}$$

The first-order condition for dealer-customer links is, as before, identical to that in the model, as these quantities only appear in Φ. The other first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial q_{dD}^a} = \frac{\partial \Phi}{\partial q_{dD}^a} \; - \; \xi^a \; = \; 0, \tag{O11}$$

$$\frac{\partial \mathcal{L}}{\partial s_+^a} = r_{CB} \; - \; \xi^a \; + \; \zeta \; + \; \mu^a \; - \; \gamma^a \; = \; 0, \tag{O12}$$

$$\frac{\partial \mathcal{L}}{\partial s_-^a} = \xi^a \; - \; \zeta \; - \; \delta^a \; = \; 0. \tag{O13}$$

For $\xi^a = -r_D^a$, the first-order condition for interdealer trade here is identical to the equivalent first-order condition in the decentralized equilibrium.

The complementary slackness conditions are as follows:

$$\mu^a \left(s_+^a - h_{CB}^a\right) \; = \; 0, \quad \gamma^a \, s_+^a \; = \; 0, \quad \delta^a \, s_-^a \; = \; 0.$$

We set the multipliers equal to the following:

$$\delta^a = \bar{r}_D - r_D^a, \quad \mu^a = \left[\bar{r}_D - r_D^a - r_{CB} \right]_+, \quad \gamma^a = \left[r_{CB} - (\bar{r}_D - r_D^a) \right]_+,$$

where $\bar{r}_D$ is the highest interdealer rate across assets. We note that each of these is weakly positive, as required of the Lagrange multipliers. Substituting these into the complementary slackness conditions and expressing s_+^a and s_-^a in terms of interdealer quantities gives:

$$
\begin{aligned}
\left[\bar{r}_D - r^a_D - r_{CB}\right]_+ \left(-\sum_d q^a_{dD} - h^a_{CB}\right) &= 0, \\
\left[r_{CB} - (\bar{r}_D - r^a_D)\right]_+ [-\sum_d q^a_{dD}]_+ &= 0, \\
(\bar{r}_D - r^a_D)\,[\sum_d q^a_{dD}]_+ &= 0.
\end{aligned}
$$

These are identical to the conditions governing use of the facility in the model, shown in equations D5 to D7. Thus if the first-order conditions for s^a_+ and s^a_- are satisfied for these values, then the set of equations that define the solution to the quadratic programme are identical to those that define the model's equilibrium.

Substituting our definitions of the multipliers into equations O12 and O13, setting $\zeta = -\bar{r}_D$ and rearranging shows that these two first-order conditions must indeed hold for these parameters. The two systems - the model solution and the optimality conditions for the quadratic programme - are therefore equivalent.

The proof from here is identical to that in Section O1. The quadratic form of the objective function ensures a minimum exists. The Hessian is exactly as in equation O6, so is positive semi-definite. The feasible set is a closed, convex, non-empty set. By the same arguments as before, the Hessian is positive definite on the feasible set if κ and σ are strictly positive. Hence the solution to this programme exists and is unique, and so the equilibrium of the model with a swap facility exists and is unique.