Essays on liquidity, stress and interventions in interbank markets

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Abstract

This dissertation comprises three chapters on banking system liquidity. The first chapter models various policies for injecting liquidity into banks during a crisis. Liquidity injections through secured lending, relative to unsecured lending or bank-debt guarantees, can better disincentivise liquidity risk taking while also mitigating ex-post capital losses, in part by limiting fire selling of securities. Asset purchases cannot credibly disincentivise liquidity risk taking. The second chapter uses Australian loan-level data to compare secured and unsecured interbank lending markets during the crisis. We find that the secured (i.e. repo) market expands to absorb heightened liquidity demand, and risky borrowers substitute into the repo market if they hold sufficient collateral. Scarcity of the highest-quality collateral pushes the repo market expansion into the next-best collateral, but risky borrowers are less capable of accessing this market. The third chapter presents and analyses an algorithm for extracting loan-level repo data from securities transactions data, to facilitate further research on repo markets.

Resumen

Esta disertación comprende de tres capítulos sobre la liquidez del sistema bancario. El primer capítulo trata modelos analíticos que exploran políticas para aumentar liquidez durante una crisis financiera. Las políticas que aumentan liquidez por medio de préstamos garantizados con aval pueden reducir la toma de riesgos de liquidez, mientras también sirven para reducir perdidas tras la crisis al reducir liquidaciones. Esto contrasta con las políticas de créditos no garantizados y las garantías de deudas bancarias. Las compras directas de activos no desincentivan de manera creíble la toma de riesgos. El segundo capítulo es empírico, y explora la experiencia de Australia durante la crisis financiera de 2007-08. Utilizando microdatos sobre préstamos interbancarios garantizados y no garantizados durante la crisis, encontramos que el mercado asegurado (es decir, de recompra) se expandió para absorber la demanda de liquidez, y que inclusive los prestatarios riesgosos pudieron acceder a ese mercado al tener suficiente garantía. La escasez de garantías de la mayor calidad causo la expansión en un mercado de recompra de menor calidad, pero los prestatarios riesgosos fueron menos capaces de accederlo. El tercer capítulo presenta y analiza un algoritmo para extraer datos de préstamos individuales (de recompra) a partir de datos de transacciones de titulas de deuda, para facilitar la investigación de los mercados de préstamos garantizados.

Preface

The financial crisis that peaked in late 2008 shook the foundations of the global financial system, and now that the dust has settled, we are left with a new perspective on banking research and regulation. While "the recent crisis was characterized by massive illiquidity" (Tirole 2011), the prospect of such a crisis was not anticipated, and accordingly, a body of research has since developed to better understand the complex nature of money markets and asset market liquidity. Regulators have responded by adding liquidity components to banks' capital requirements, instructing them to hold sufficient 'high quality liquid assets' to withstand a substantial adverse liquidity shock. But these developments in research and regulation are relatively young, and there is still much to learn.

This dissertation advances our understanding by analysing the role of collateral in banks' liquidity management. The first chapter presents a theoretical model to demonstrate that the impacts of a central bank or government's liquidity injections during a crisis can crucially depend on how the intervention is collateralised. The second chapter analyses loan-level data on collateralised and uncollateralised interbank markets during the crisis, revealing substantial differences in these two markets' behaviour. The third chapter puts forwards a method for compiling more detailed data on collateralised interbank markets.

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Chapter 1

LIQUIDITY INJECTION POLICIES, FIRE SALES AND COLLATERAL

1.1 Introduction

How should bailouts for liquidity-stressed banks be provided, taking into account their immediate impact and the incentives they generate? In late 2008, the world's largest banking systems experienced a rapid decline of private-sector funding liquidity, alongside fire sales and a dry up of market liquidity for many securities. Banks with insufficient cash or high-quality liquid assets had difficulty meeting their short-term liabilities, and authorities responded with massive liquidity injections. Authorities were aware that this could damage banks' incentives to manage their own liquidity risk but considered avoiding imminent and widespread bank failures to be a higher priority.[1]

For example, in the peak-stress period US authorities granted banks upwards of 430 billion USD additional secured lending – also known as collateralised lending or repo (short for 'repurchase agreement'), under which the borrower must provide collateral, typically securities, to the lender for the life of the loan. US authorities also subsidised around 330 billion USD of banks' unsecured lending by purchasing their commercial paper and guaranteeing their debt, and spent around 155 billion USD on capital injections. The European Central Bank (ECB) increased secured lending to banks by around 340 billion EUR, while euro area countries guaranteed close to 770 billion EUR of banks' unsecured debt and implemented capital injection programs with a combined cap of 140 billion EUR.

[1]For example, see Bernanke (2008).

The Bank of England increased secured lending to banks by at least 365 billion GBP and purchased around 100 billion GBP of securities, while the UK Government guaranteed up to 250 billion GBP of banks' unsecured debt and injected up to 86 billion GBP of capital into banks.[2]

Evidently, authorities have various liquidity-injection policies at their disposal and during 2008 and 2009 heavily relied on expansion of secured lending, also the standard tool of open market operations during normal times. Several questions naturally arise, which this paper seeks to address. Was the heavy use of secured lending justified? Do different means of liquidity provision give banks different incentives regarding liquidity risk? Do other impacts on the financial system vary across policies?

The model presented in this paper demonstrates that liquidity injection through secured lending can combine two desirable features that other forms of emergency funding cannot: penalties for emergency funding that disincentivise ex-ante liquidity-risk taking, and mitigation of fire sales and in turn banks' securities-portfolio losses. To contain incentives for liquidity-risk taking, a lending policy should charge interest rates high enough to deter unnecessary borrowing, in line with Bagehot (1873)'s suggestion, throughout this paper referred to as 'penalty rates'. Penalty rates encourage banks to sell securities rather than borrow, which under an unsecured lending policy pushes down securities prices. However, under a secured lending policy banks' selling is constrained by their need to post securities as collateral, forcing banks to rely more on borrowing at the penalty rate, and mitigating securities price depression. Relative to unsecured lending, the stronger impact of penalty rates and higher securities prices and can better deter liquidity risk taking while also leaving banks better off ex-post.

Previous papers that compare bank-bailout policies do not explicitly compare policies aimed at preventing illiquidity-driven failures, and tend to focus on policies' ex-post consequences rather than incentives generated. Acharya and Yorulmazer (2008) and Acharya et al. (2011) show that incentives differ depending on which banks receive liquidity, but neither compare more than one alternative for preventing bank failures, focusing instead on preventing inefficient asset liquidation. He and Krishnamurthy (2013) also focus on liquidity-affected asset prices, comparing the ex-post effects of lending, asset-purchase and capital-injection policies. Philippon and Schnabl (2013) and Farhi and Tirole (2012) consider policies aimed at stimulating bank lending. The former analyse the optimal design for a capital-injection policy, and the latter compare the ex-post implications of system-wide

[2] Appendix 1.6.1 provides more details on the US and Europe figures in this paragraph.

and bank-specific funding subsidisations. Like this paper, Ashcraft et al. (2011) explicitly model secured lending during a crisis – arguably the most used intervention during the 2008 liquidity crisis – comparing the effect on securities prices of a change in haircuts and interest rates.

This paper considers four types of liquidity injections: lending to banks unsecured or, similarly, guaranteeing banks' newly issued unsecured debt; lending to banks against securities as collateral; buying securities that banks hold to raise the securities' market price; or injecting capital. For a given policy type, the authority sets parameters such as the interest rate to achieve an optimal balance of financial stability, i.e. crisis probability, and economic growth, i.e. bank profitability. The policy parameters are assumed credible only if they do not lead to bank failures. Farhi and Tirole (2012) demonstrate the credibility problem for an authority that aims to deter banks from taking liquidity risk, but when a high level of risk is nonetheless taken and a crisis occurs, is not willing to suffer a fall in banks' profits. This paper assumes the authority cares more about bank profits in the midst of a crisis – when losses could lead to a systemic failure – whereas, for example, charging banks penalising interest rates is credible if they can repay when they are liquid. This assumption is supported by the widespread support for the Bagehot (1873) 'penalty rates' dictum, and the fact that penalty rates also benefit the authority by deterring excessive use of its balance sheet (which is indeed Bagehot's justification).

In this paper a liquidity crisis is the culmination of three model characteristics: banks ex-ante choose the liquidity risk of their asset portfolio; less-liquid assets have shallower markets, i.e. imperfect *market liquidity*; and banks can experience a random outflow of short-term liabilities, i.e. a withdrawal of *funding liquidity*. If a large funding-liquidity withdrawal occurs and banks are holding assets that are not sufficiently liquid, the amount of selling required to meet the withdrawal potentially pushes prices down to the point where their sales cannot raise enough cash. In this case banks are solvent yet illiquid – i.e. they have positive future net worth but are unable to meet payment obligations – and the authority intervenes through one of the four policies.

This relatively simple crisis anatomy yields some important distinctions between secured lending and other forms of liquidity injection, aside from risk taken by the authority, that are reasonably intuitive but have not been highlighted by previous literature. First, if penalty rates are charged, securities-market prices will be higher under a secured lending policy than under other funding policies because banks' securities liquidation is restricted by the amount of collateral they must post. Ashcraft et al. (2011) show that a central bank's expansion of secured lending (via lowering haircuts) can raise market prices, because banks find it cheaper to fund a security's purchase by using it as collateral to borrow rather than by funding it with one's own capital. This paper demonstrates that lowering the cost of funding is not necessary for a secured lending policy to improve illiquid securities markets. Rather, the collateral requirement forces banks to treat emergency borrowing and the securities market as substitutes (as opposed to complements as in Ashcraft et al. (2011)). The more scarce is liquidity, the greater is the role played by the authority's balance sheet – which is immune to liquidity spirals – in replacing the liquidity provision function of securities markets.

Penalty rates are defined here as interest rates high enough for banks to avoid unnecessary use of emergency funding, subject to avoiding failure. Bagehot (1873) advises charging penalty rates to minimise use of the central bank's balance sheet, which in his time faced constraints that made it subject to runs. This model demonstrates that if an authority intervenes by lending, the same interest-rate condition is required to disincentivise banks against ex-ante maximising their liquidity exposures, as also argued by, for example, Fischer (1999). In this mode, absent penalty rates, emergency funding is cheaper than private liquidity sources, so the ex-post marginal cost of a liquidity exposure is lower conditional on requiring a bailout than conditional on a bailout not being available. Since banks can raise the probability of requiring a bailout by increasing their liquidity exposure, an absence of penalty rates implies that the expected cost of liquidity exposures during a crisis can be reduced by taking more liquidity risk.

For a given penalty rate, the model shows that a secured lending policy more strongly deters liquidity exposures than an unsecured lending policy, because for a given liquidity shortage, the collateral requirement makes banks sell fewer securities, and therefore borrow more at the penalty rate. Nevertheless, the greater borrowing does not leave banks with lower profit after the crisis, because they receive a better price for the securities they do sell. Importantly, the higher market price offsets the profit effect but not the disincentive effect of the penalty rates, because it more strongly benefits banks with relatively low liquidity exposures. These banks borrow less from the authority, and are therefore less constrained by collateral requirements in participating in the securities market. Accordingly, relative to an unsecured lending equilibrium, a secured-lending equilibrium can have lower ex-ante liquidity exposures, that is, lower probability of bank failures, as well as higher expected ex-post profits. Another implication is that, for a given liquidity exposure, a secured-lending policy involves greater use of the authority's balance sheet (although most likely with less risk); however, this is to some extent offset if banks have lower liquidity exposures during the crisis.

In the model, the securities purchase policy involves the authority buying securities to offset the price effect of banks' selling pressure, preventing prices from falling far enough to cause widespread distress. The results demonstrate that the authority is incapable of deterring liquidity risk, because the securities market price must be relatively favourable to banks, to transfer them enough liquidity to avert failure. The authority could attempt to induce a low-exposure equilibrium by ex-ante claiming that, given a crisis, it would intervene in the securities market only to a limited extent. However, as in Farhi and Tirole (2012), such equilibria are not credible, because if banks nonetheless carry high exposures, the authority's objective of saving banks forces it to support the securities market more than it had claimed. Indeed, under a securities purchase policy individual banks' liquidity-risk exposures are strategic complements. In constrast, the lending policies can credibly deter liquidity risk taking because the authority is more willing to impose costs on banks after the crisis conditions ease. The model therefore highlights that a crucial component of credible and penalising liquidity injection policies is that liquidity is provided for sufficiently long terms.

During the crisis in 2008 and 2009 central banks and governments also injected large quantities of capital into banks. Authorities effectively purchased ownership in banks, typically selling it back later at a price reflecting the banks' post crisis profitability. This policy is modeled as a provision of cash to the bank in return for a proportion of of its post-crisis assets, with the proportion increasing in the quantity of cash provided. The model highlights that capital injections more heavily penalise high-quality banks, incentivising banks with low-quality assets to take higher liquidity risk than others. For the same reason, it is less likely to leave low-equity banks ex-post insolvent. To ensure banks remain solvent ex-post, the authority can offer a combination of capital injections and either an unsecured or secured lending policy, and the model indicates that the features of lending policies described above are maintained when combined with capital injections.

The rest of this paper has four sections. Section 1.2 presents the model framework and describes the key assumptions. Section 1.3 sets up a bank's payoff function and section 1.3.1 applies it to an unsecured lending policy, which is used as a benchmark for analysing the secured lending and securities purchase policies in sections 1.3.2 and 1.3.3. Section 1.4 comprises further applications and extensions. In section 1.4.1 capital injection policies are examined, both in isolation and in combination with lending policies. Sections 1.4.2 and 1.4.3 relax two stylised features of the model – that the authority minimises its haircuts on secured lending and that no interbank transactions occur in equilibrium – to argue that the results are not fundamentally changed. Section 1.5 concludes by discussing the paper's results in light of liquidity-injection policies adopted by US and European authorities around late 2008. Appendix 1.6.1 provides more details of these policies and the proofs are in appendix 1.6.2.

1.2 The model

This section first describes the model's high-level structure, then each of the components are discussed in more detail in sections 1.2.1, 1.2.2 and 1.2.4. There are three dates, $t = 0, 1, 2$, and four types of agents: the authority, a continuum of risk-neutral banks, external creditors, and securities buyers.

For a given type of liquidity injection policy, at date 0 the authority optimises its policy parameters, such as the interest rate on emergency lending. Banks then choose their liquidity risk to maximise their expected date 2 payoff Π_i, taking policy parameters as credible if the policy does not result in bank failures.

At date 1 external creditors potentially withdraw an exogenous random quantity of liquidity from banks. Banks can raise extra liquidity by selling securities to securities buyers, at a market price that equilibrates banks' liquidity demand with securities buyers' optimal liquidity supply given their outside investment options. If a bank cannot raise sufficient liquidity, the authority intervenes.

At date 2, if there was a credit withdrawal at date 1, liquidity returns to the securities market and banks repay any obligations to the authority. If there was not, securities pay positive net returns.

1.2.1 Banks and external creditors

At date 0 the continuum of risk-neutral banks each have a liquid endowment l, which they can allocate between two types of liquid assets – securities 's' and cash 'c'. Securities have positive expected net returns but in some states of the world market illiquidity causes their price to fall. Cash has zero net return but always holds its value. Denote bank i's securities choice by s_i. The date 0 price of securities is normalised to 1 so $c_i + s_i = l$ for all i.

This investment decision resembles the classic portfolio decision in Diamond and Dybvig (1983). The liquid endowment l can be interpreted as early returns on investments. Cash c_i represents cash and highly liquid low-return securities such as government bonds, whereas securities can be thought of as relatively safe privately-issued debt. This simplifying dichotomy resembles how liquidity-risk management is interpreted by the Liquidity Coverage Ratio (LCR) of Basel III, which requires banks to hold a sufficient quantity of high-quality assets with low market-liquidity risk, distinguishing them from lower quality securities.[3] It is also motivated by the fact that banks had high exposures to assets that had liquid markets before the crisis, but that became illiquid during the crisis. This has been documented with respect to private secured-lending markets by Hordähl and King (2008) and Gorton and Metrick (2012a), and with respect to asset-backed securities markets by Brunnermeier (2009) and many others.

Denote the set of choices (i.e. the strategy profile) of any unit measure of banks that excludes bank i as s_{-i}, and the set of all banks' choices as s, which can be thought of as the mapping $s : [0,1] \to [0,l]$, and is assumed nondecreasing and integrable in i. The aggregate mass of securities held by banks is defined as the scalar $S = \int_0^1 s_i di$. The statement $s_{-i} = S$ denotes that the measure of banks that each hold S is one (i.e. an 'almost' symmetric choice), and $s_{-i} \neq S$ denotes that the measure choosing S is less than one. The statement $s = S$ implies a fully symmetric choice outcome.

At date 1, with probability $1 - \lambda$ such that $0 < \lambda < 1$, nothing happens and at date 2 securities are worth $1 + r_s > 1$. With probability λ there is a liquidity withdrawal by *external creditors*, whereby each bank has the same cash obligation b that is randomly drawn from positive continuous density $f(b)$ defined on $[0,l]$. In this case external creditors also take liquidity from the securities market by selling γb value of securities, where $\gamma > 0$.[4] This funding liquidity withdrawal is similar to much of the banking literature including Diamond and Dybvig (1983), and can be interpreted as short-term creditors not rolling over debt, withdrawing depositors, credit-line draw downs, or, similar to the immediate cause of AIG's

[3]The Basel Committee for Banking Supervision summarises the LCR as follows: "the objective of the LCR is to promote the short-term resilience of the liquidity risk profile of banks. It does this by ensuring that banks have an adequate stock of unencumbered high-quality liquid assets (HQLA) that can be converted easily and immediately in private markets into cash" (Basel Committee for Banking Supervision, 2013, paragraph 1). The approach also matches Saunders and Cornett (2007)'s textbook definition of liability-side liquidity risk management: "When liability holders demand cash by withdrawing deposits, the [financial institution (FI)] needs to borrow additional funds or sell assets to meet the withdrawal. The most liquid asset is cash; FIs use this asset to pay claim holders who seek to withdraw funds. However, FIs tend to minimize their holdings of cash reserves as assets because those reserves pay no interest. To generate interest revenues, most FIs invest in less liquid and/or longer maturity assets. While most assets can be turned into cash eventually, for some assets this can be done only at a high cost when the asset must be liquidated immediately. The price the asset holder must accept for immediate sale may be far less than it would receive with a longer horizon over which to negotiate a sale" (pages 493-494).

[4]External creditors' sales γb ensure that if in a severe crisis banks are posting all their securities to the authority as collateral, there is still some selling pressure in the securities market and therefore some liquidity distress (section 1.3.2).

liquidity distress in 2008, unexpected margin requirements.

1.2.2 Securities buyers and the date 1 securities market

Given a liquidity withdrawal, if $c_i < b$ then bank i must satisfy its cash shortfall by selling securities to *securities buyers* or banks with spare cash. Securities buyers maximise profit by allocating their cash between securities purchases and an outside investment with finite and continuously decreasing returns. Assume that securities buyers have at least $l(1+\gamma)$ cash prior to date 1, that if they invest all their cash in the outside investment its net return is zero, and that they can short sell unlimited securities if the price is not below 1. Define the market clearing securities price as $1 - m^*$ with m^* termed *market illiquidity*, and securities buyers' optimal cash spent on securities purchases as $L_S(m)$. The assumptions on securities buyers imply:

$$L_S(m) = \begin{cases} [-\infty, 0] & \text{if } m = 0 \\ L_S^+(m) & \text{if } m > 0, \end{cases} \tag{1.1}$$

where $L_S^+(0) = 0$, dL_S^+/dm is positive and continuous, and $0 \leq m^* < 1$.

Denote the demand from banks and external creditors for liquidity from the securities market by the function $L_D(b, s, m)$, whose specific form depends on the policy implemented. In general, L_D can be expressed

$$L_D = \int_i L_i di, \tag{1.2}$$

where L_i is bank i's demand for liquidity through securities sales. Date 1 securities market equilibrium requires that m^* satisfies

$$L_S(m^*) = L_D(b, s, m^*)$$

where b is exogenous and banks choose s at date 0. Figure 1.1 illustrates m^* for two different L_D schedules (which resemble the functional form in expression 1.4 later in this section). The lower market illiquidity $m_0^* = 0$ is characterised by banks buying securities from external creditors and securities buyers, whereas at m_1^* banks and external creditors are selling securities to securities buyers. The kink in L_D^1 occurs where banks are liquidating all their securities and higher m implies less liquidity can be obtained.

To simplify notation, m^* will sometimes be characterised by the inversion of the L_S function, denoted M, such that $m^* = M(L_D) \equiv L_S^{-1}(L_D)$. The assumptions on L_S imply that $M(L_D) = 0$ for all $L_D \leq 0$, $M(l + \gamma l) < 1$, and that the first derivative of M, sometimes denoted M', is continuous and positive for all $L_D > 0$. The general expression for equilibrium market illiquidity used throughout this paper is $m^*(b, s_{-i})$, writing s_{-i} to highlight the fact that no zero measure of banks can affect the equilibrium price. The implicit function $m^*(b, s_{-i})$ is shown to be well defined in each case examined.

Securities-market illiquidity is the key market imperfection in this model; banks would not become distressed if securities could always be liquidated at net present value. The equilibrium mechanism is a generalisation of the cash-in-the-market pricing of Allen and Gale (1994) such that the external supply of cash available to buy securities continuously increases as the market price falls, as in the securities market of Diamond and Rajan (2011). Ample liquidity is assumed to return to the market at a later date, bringing the securities price back to its net present value. Liquidity-driven selling can therefore push prices below their arbitrage-free counterparts, consistent with empirical studies of securities prices such as Coval and Stafford (2007), Hameed et al. (2010) and Longstaff (2010).

Funding liquidity and market liquidity are linked by the constraint that if a bank's outflow of short-term liabilities cannot be funded by cash, it must be met by liquidating assets. This link is why the LCR requires banks to hold a quantity of high-quality liquid assets that depends on their short-term liabilities. It is empirically documented by Nyborg and Östberg (2014), who term such securities liquidation as 'liquidity pullback', and by Fontaine and Garcia (2011). This mechanism, also modelled by Diamond and Rajan (2011), resembles the 'liquidity spiral' in Brunnermeier and Pedersen (2009) whereby to meet a tightened capital constraint, investors must sell assets, pushing down the asset price and further reducing the value of their capital value.

The date 1 value of bank i's liquid assets is $c_i + s_i(1 - m^*) = l - s_i m^*$, so bank i's date 1 *liquidity position* is $l - s_i m^* - b$. Denote this liquidity position as l^1, i.e.

$$l^1(b, s_i, s_{-i}) = l - s_i m^*(b, s_{-i}) - b.$$

Refer to the liquidity withdrawal that expends precisely all of bank i's liquidity assets, such that $l^1 = 0$, as $\bar{b}_i = \bar{b}(s_i, s_{-i})$. Specifically, the implicit function $\bar{b}_i$ is defined by

$$\bar{b}_i = l - s_i m^*(\bar{b}_i, s_{-i}), \tag{1.3}$$

which is shown to be well-behaved in each case examined. If $b \leq \bar{b}_i$, the net value of securities that bank i sells is equal to $b - c_i$; banks are assumed to buy at date 1 if they have spare cash and are indifferent between buying and selling.

If $b > \overline{b}_i$ bank i is *liquidity deficient* and the authority intervenes to prevent its failure. Consider the case with $s_{-i} = S$ and banks selling all their securities when liquidity deficient. Market illiquidity takes the form

$$m^* = \begin{cases} M(b + S - l + \gamma b) & \text{if banks are not liquidity deficient } (\equiv m^*_{\mathcal{G}}(b, S)) \\ M(S(1 - m^*) + \gamma b) & \text{if banks are liquidity deficient } (\equiv m^*_{\mathcal{U}}(b, S)). \end{cases} \tag{1.4}$$

If $s_{-i} \neq S$ then for some b and S, the liquidation value L_D depends on how much of S is held by banks that are liquidity deficient at that b. It follows that the effect of s_{-i} on m^* cannot be fully represented by S, so in general market illiquidity is referred to as $m^*(b, s_{-i})$.

Figure 1.2 illustrates the timeline of events that banks face when choosing their securities holdings.

1.2.3 An example of m^* and $\overline{b}$

Consider the market illiquidity function

$$M(L_D) = \max\{\alpha L_D, 0\}$$

where $0 < \alpha < 1/(l + \gamma l)$. Assume that $s_{-i} = S$ and that banks liquidate all their securities when liquidity deficient, so market illiquidity is as characterised in expression 1.4. Denoting the b at which the unit measure of banks becomes liquidity deficient as $\overline{b}_S$, market illiquidity satisfies

$$m^*(b, S) = \begin{cases} 0 & \text{if } b \leq \frac{l-S}{1+\gamma} \\ \alpha(b + S - l + \gamma b) & \text{if } \frac{l-S}{1+\gamma} < b \leq \overline{b}_S \\ \frac{\alpha S + \gamma b}{\alpha S + 1} & \text{if } b > \overline{b}_S. \end{cases} \tag{1.5}$$

From expression 1.3, the threshold $\overline{b}_S$ can be solved as

$$\overline{b}_S = \frac{l + \alpha S(l - S)}{1 + \alpha S(1 + \gamma)}. \tag{1.6}$$

Figure 1.3 plots the market illiquidity function in expression 1.5 for two fixed values of S such that $0 < S' < S'' < l$. Below the first kink at $b = (l - S)/(1 + \gamma)$, banks are buying more than the value of securities that external creditors are selling (γb) and market illiquidity is zero, as is the case for m^*_0 in Figure 1.1. Above the second kink at $b = \overline{b}_S$, banks are liquidity deficient and are selling all their securities to securities buyers, with the positive slope driven by external creditors also selling γb. When S increases, market illiquidity rises at all $b > (l-S)/(1+\gamma)$ and both kinks shift left.

Also shown is bank i's capacity to survive market illiquidity $(l-b)/s_i$ for two fixed values of s_i such that $0 < s_i' < s_i'' = l$. The intersection of of m^* and $(l-b)/s_i$ determines $\overline{b}_i$ because bank i avoids liquidity deficiency if and only if $(l-b)/s_i \geq m^*$. If $s_i > 0$ then at $b = l$ bank i cannot survive any market illiquidity because the liquidity withdrawal requires its full date 0 liquid endowment. An increase in s_i pivots bank i's illiquidity capacity anti-clockwise around $(l, 0)$, lowering its $\overline{b}_i$ and reducing its probability of avoiding liquidity deficiency for any given S.

1.2.4 The authority and liquidity injection policies

The model outcomes are compared across four types of liquidity injection policies $\mathcal{P}$. The authority has full information and, given policy $\mathcal{P}$, announces the policy parameters pp (such as the interest rate) at the start of date 0. At date 1, banks accept a liquidity injection rather than fail; a sufficiently high cost of failure would induce the same results. The policy parameters are chosen optimally reflecting lexicographic preferences, with priorities:

1. Providing just enough liquidity to prevent any bank failures.

2. Maximising the objective function W on equilibrium liquidity risk S and expected date 2 bank capital $\Pi \equiv \int_i \Pi_i di$.

The preference represented by W is assumed time consistent. Otherwise the authority could, for example, announce penalty rates in an attempt to induce low liquidity risk, then at date 1 charge lower rates than it announced in order to increase banks' profits. The incentives generated by the policy parameters can be thought of as representing the setting of expectations for future liquidity crises, which supports an assumption of time consistency. The assumption is also supported by the common acceptance among central bankers of penalty rates as credible, and that penalty rates have the additional ex-post benefit of deterring unnecessary use of the central banks' balance sheet (both are views maintained by Bagehot (1873)). In contrast, the preference for preventing bank failures is assumed to be strictly maintained each period, representing the authority's primary objective of avoiding a systemic event.

The objective function W is

$$W(pp) \equiv w_1(S(pp)) + w_2(\Pi(pp)) \tag{1.7}$$

with $w_1' < 0$ and $w_2' > 0$. Given that each policy maintains the preference for preventing bank failures, the policies can be compared by their optimum W.

Three types of optimal policies $(\mathcal{P}, pp)$ are analysed:

1. **Unsecured lending** $(\mathcal{U}, r_{\mathcal{U}})$: the authority lends each bank enough to avoid failure, with repayment at date 2 of principal plus interest at rate $r_{\mathcal{U}}$.
2. **Secured lending** (or **repo**) $(\mathcal{R}, r_{\mathcal{R}})$: the authority lends each bank enough to avoid failure, provided that the bank collateralises its borrowing with a sufficient quantity of securities, with repayment at date 2 of principal plus interest at rate $r_{\mathcal{R}}$.
3. **Securities purchase** $(\mathcal{S}, m^{\mathcal{S}}(b))$: the authority determines an acceptable schedule of market illiquidity $m^{\mathcal{S}}(b)$ and purchases sufficient securities such that the date 1 market price does not fall below $1 - m^{\mathcal{S}}(b)$.

Section 1.4.1 also analyses a capital injection policy without any policy parameters.

1.3 Optimal Policies and Bank Responses

Under policy $\mathcal{P}$, taking policy parameters as given, bank i's payoff $\Pi_i^{\mathcal{P}}(s_i, s_{-i})$ depends on its own securities choice s_i and the set of choices of other banks s_{-i}. It is the expected gross return on liquid assets across three possible outcomes: no liquidity withdrawal, a liquidity withdrawal that the bank can satisfy with its liquid assets, or a liquidity withdrawal with b high enough that the bank is liquidity deficient and requires an intervention.

$$\begin{aligned}
&\Pi_i^{\mathcal{P}}(s_i, s_{-i}) = (1-\lambda)(l + s_i r_s) \\
&+\lambda\Bigg(E_b\Big[\underbrace{(\text{liquidity position})}_{l - s_i m^*(b, s_{-i}) - b} * \underbrace{(\text{return on liquidity})}_{\frac{1}{1-m^*(b,s_{-i})}} \Big| \underbrace{\text{sufficient liquidity}}_{b \leq \bar{b}(s_i, s_{-i})}\Big] * pr(\text{sufficient liquidity}) \\
&\quad + E_b\Big[\underbrace{(\text{liquidity position})}_{l - s_i m^*(b, s_{-i}) - b} * \underbrace{(\text{return on liquidity})}_{\text{determined by authority}} \Big| \underbrace{\text{liquidity deficient}}_{b > \bar{b}(s_i, s_{-i})}\Big] * pr(\text{liquidity deficient})\Bigg)
\end{aligned} \tag{1.8}$$

In general, a bank's gross return on liquid assets given a liquidity withdrawal is its liquidity position times the *return on liquidity*. The return on liquidity is the value of cash at date 1. If $b \leq \bar{b}_i$ the return on liquidity is $1/(1 - m^*)$, which is the quantity of securities purchased (if $b < c_i$) or not sold (if $b \geq c_i$) per unit of liquidity position, multiplied by the date 2 value of each security (which equals one). If the liquidity position is negative, the return on liquidity is the cost of sourcing liquidity from the authority and is proportional to the size of the deficit.[5]

Each bank chooses s_i by comparing the returns that securities give in the normal state r_s against the expected costs given a liquidity withdrawal. These costs depend on how many securities other banks hold because higher S (holding its composition constant) causes more selling pressure, and therefore market illiquidity, whenever b is high enough such that $m^* > 0$. Higher market illiquidity lowers the expected marginal return to securities, since depressed prices raise the value of spare cash if $b < c_i$ and the cost of having to sell securities if $b > c_i$. Accordingly, as S increases, securities' expected returns decrease, typically permitting a fixed point where optimal s_i given S is equal to S, so that acting in line with other banks is the best response to their choices.

Denote by $s^*_{i,\mathcal{P}}(s_{-i}, pp)$ the set of optimal choices of securities for bank i given the choices of other banks and the policy parameters; that is,

$$s^*_{i,\mathcal{P}}(s_{-i}, pp) = \arg\max_{s_i} \ \Pi_i^{\mathcal{P}}(s_i, s_{-i}, pp).$$

Definition *For policy $\mathcal{P}$ and parameters pp, a (Nash) equilibrium set of securities choices $s^*_{\mathcal{P}}$, with corresponding aggregate securities holdings $S^*_{\mathcal{P}}$, is one that satisfies $s_i = s^*_{i,\mathcal{P}}(s^*_{-i,\mathcal{P}}, pp)$ for all i.*

The $\mathcal{P}$ subscripts will sometimes be dropped when there is no ambiguity.

Banks are ex-ante homogeneous but asymmetric strategies, for example if some banks held more cash to arbitrage potential date 1 market illiquidity, are not explicitly ruled out. Asymmetric pure-strategy choices, defined by $s_i \neq S$ for some i, can be equivalently interpreted as symmetric mixed strategies, because the continuum of banks ensures that the distribution of choices observed corresponds exactly to their probabilities under the mixed strategies. The following uses the terminology 'a/symmetric' rather than mixed and pure strategies.

[5] As outlined in section 1.2.4, under the unsecured and secured lending policies the authority is assumed to only lend banks the minimum they need to avoid failure, which forces them to sell all their securities even if they would prefer to use more emergency funding instead. Without this assumption there would be two possible outcomes: the interest rate is high enough that banks still minimise borrowing, or it is not, and banks borrow enough to reduce their securities selling to the point where the cost of selling at $1 - m^*$ is equal to the borrowing cost imposed by the authority. This paper focuses on the first type of outcome in which banks would choose to minimise their borrowing, where the assumption is of no consequence. In the second possible outcome, a lower interest rate on emergency borrowing would lead to corner solutions with maximum liquidity exposures, although the solution is complicated by the fact that a bank's ex-post payoffs would discontinuously increase at the b at which emergency lending becomes available.

1.3.1 Unsecured lending

Under an unsecured lending policy the authority's policy parameter is the interest rate $r_{\mathcal{U}}$. In order to draw results from bank i's payoff function, Lemma 1 shows that the the implicitly defined functions $m^*(b, s_{-i})$ and $\bar{b}(s_i, s_{-i})$ are sufficiently well behaved.

Lemma 1 *Under the unsecured lending policy, the implicit functions m^* and $\bar{b}$ are unique, Lipschitz continuous in scalar arguments (e.g. in S if $s_{-i} = S$), and everywhere permit generalised derivatives as defined by Clarke (1975). Further, m^* is nondecreasing in b and, if $s_{-i} = S$, in S, and $\bar{b}$ is strictly decreasing in s_i and, if $s_{-i} = S$ and $s_i > 0$, in S.*

Proof. See Appendix.

Lemma 1 permits the payoff function

$$\Pi_i^{\mathcal{U}}(s_i, s_{-i}) = (1-\lambda)(l + s_i r_s) + \lambda\left[\int_0^{\bar{b}(s_i,s_{-i})} \frac{l^1(b, s_i, s_{-i})}{1 - m^*(b, s_{-i})} f(b)db + \int_{\bar{b}(s_i,s_{-i})}^{l} l^1(b, s_i, s_{-i})(1 + r_{\mathcal{U}})f(b)db\right]. \tag{1.9}$$

Define $r_{pen} \equiv M(l+\gamma l)/(1-M(l+\gamma l))$, where $M(l+\gamma l)$ is the least upper bound on market illiquidity, corresponding to $S = b = l$. If $r_{\mathcal{U}} \geq r_{pen}$ then banks find sourcing liquidity from the authority more expensive than through the securities market. This condition ensures that if a bank marginally increases its securities holdings, which raises the probability that it needs to borrow from the authority, its ex-ante marginal return to securities decreases. In other words, it ensures that a bank cannot increase its marginal return to securities by increasing its liquidity risk.

Assumption ***(Optimal penalty rates).*** *The authority places enough weight on financial stability objectives, i.e. on S, to set the policy interest rate above r_{pen}.*

Assumption 2 will be maintained throughout the paper for both unsecured and secured lending policies. As a simple example, an objective function W would give optimal penalty rates if w_2 is linear while w_2 is concave, with $-w_1' > w_2'$ whenever S is above some threshold that can only be induced by penalty rates.

Proposition 3 *The optimal unsecured lending policy induces a unique and symmetric equilibrium S^* that is interior for a range of model specifications.*

Proof. See Appendix.

Banks' equilibrium securities holdings reflect the typical risk-return tradeoff. They are increasing in non-crisis expected returns r_s. They are decreasing in securities' liquidity risk, represented by the sensitivity of m^* to b, and in the interest rate charged by the authority on emergency borrowing.

Penalty rates are sufficient but not necessary for Proposition 3; bank i's profits are strictly concave in its securities holdings as long as $r_{\mathcal{U}} > m^*/(1-m^*)$ for equilibrium values of m^*, and strict concavity is also a sufficient but not necessary condition. The optimal penalty rates condition aligns with Bagehot's recommendation that the interest rate on emergency lending should be high enough that banks do not borrow more than they need. Bagehot's recommendation therefore also ensures that banks cannot raise their marginal benefits from liquidity exposures by increasing their exposures, an outcome that would lend itself to excessive liquidity-risk taking and high likelihoods of banking crises occurring.

During the 2008 liquidity crisis, some authorities priced emergency lending facilities through auctions in which the total amount of funds was predetermined, banks' bids comprised quantities and interest rates, and the final auction rate was set at the lowest-priced bid that was high enough to receive some funds (appendix 1.6.1 provides some examples). It is interesting to consider whether such rates would have been penalising. The model indicates that if the total quantity auctioned exceeds the quantity that banks' need $l - b - Sm^*$, banks' marginal willingness to pay for funds, and thus the auction rate, would fall to $m^*/(1-m^*)$ which would then itself be decreasing in the quantity of funds auctioned. This would not be a penalising intervention, because the auction rate is below the cost of liquidity that prevails without intervention. Alternatively, an auction mechanism that price discriminates based on each bank's willingness to pay for funds may better penalise banks that would fail without intervention.

1.3.2 Secured lending

Under a secured lending policy, the authority sets the policy parameter $r_{\mathcal{R}}$. A liquidity-deficient bank must use some of its securities as collateral for borrowing from the authority, and therefore sells less. In essence, the policy works by raising the amount of liquidity that a bank extract from its securities holdings. A security's 'liquidity value' if sold is the illiquid price $1 - m^*$, and if used as collateral is $1 - h$ where h is the haircut set by the authority. Thus, for the policy to raise securities' liquidity value enough to save banks, h must be sufficiently below m^*. This section assumes that the authority sets the lowest h that eliminates its principal risk, being $h = 0$, so securities retain full liquidity value if used as collateral. Higher haircuts are examined in section 1.4.

When liquidity deficient, bank i's allocation of securities to collateral s_{ri} and to sales s_{mi} is pinned down by the authority's desire to minimise lending. That is, the authority ensures that s_{ri} is at the lowest value that satisfies

$$s_{ri} + s_{mi}(1 - m^*) \geq b - c_i \tag{1.10}$$

such that $s_i \geq s_{ri} + s_{mi}$ and $s_{ri} \geq 0$ and $s_{mi} \geq 0$. Since bank i is liquidity deficient, i.e. $s_i(1 - m^*) < b - c_i$, the quantity of securities used as collateral satisfies

$$s_{ri} = s_i - s_{mi} = s_i - \frac{l - b}{m^*}. \tag{1.11}$$

If the authority did not minimise lending, penalty rates would still imply that banks minimise their borrowing, resulting in the same value for s_{ri}. Either way, the quantity of securities sold $(l - b)/m^*$ does not depend on securities held s_i, because for $s_i > (l - b)/m^*$, any increase in s_i and corresponding reduction in c_i raises bank i's borrowing needs one for one, so the additional securities are just used as collateral for borrowing.

When bank i borrows from the authority, securities sales s_{mi} are decreasing in b because the higher a bank's liquidity deficit, the more it must maximise its securities' liquidity value by using them as collateral. Market illiquidity is therefore potentially decreasing in the liquidity withdrawal size, as banks' large collateral requirements mean few securities are left over to be sold. Equilibrium would be more complicated if it was possible that at high b market illiquidity was low enough for a bank's liquidity deficit to return to surplus. Lemma 4 shows that the negative, direct effect of b on a bank's liquidity position $l - b - s_i m^*$ is necessarily stronger than the potentially positive, indirect effect through m^*, and that more generally m^* and $\overline{b}_i$ are well behaved.

Lemma 4 *Under the secured lending policy, the implicit functions m^* and $\overline{b}$ are unique, Lipschitz continuous in scalar arguments (e.g. in S if $s_{-i} = S$), and everywhere permit generalised derivatives as defined by Clarke (1975). Further, m^* is nondecreasing in S if $s_{-i} = S$, and $\overline{b}$ is strictly decreasing in s_i and, when $s_i > 0$, nonincreasing in S.*

Proof. See Appendix.

Lemma 4 permits bank i's objective function

$$\Pi_i^{\mathcal{R}}(s_i, s_{-i}) = (1-\lambda)(l + s_i r_s)$$
$$+ \lambda \left[\int_0^{\bar{b}(s_i, s_{-i})} \frac{l^1(b, s_i, s_{-i})}{1 - m^*(b, s_{-i})} f(b) db + \int_{\bar{b}(s_i, s_{-i})}^{l} l^1(b, s_i, s_{-i}) \frac{r_{\mathcal{R}}}{m^*(b, s_{-i})} f(b) db \right]. \tag{1.12}$$

Given liquidity deficiency, a bank's date 2 payoff is affected positively by the value of securities it still owns s_{ri} and negatively by the date 2 repayment $s_{ri}(1 + r_{\mathcal{R}})$, leaving the net loss at $s_{ri} r_{\mathcal{R}} = l^1 r_{\mathcal{R}}/m^*$. The return on liquidity is therefore $r_{\mathcal{R}}/m^*$. It is the interest cost on necessary borrowing, because collateralising one unit of borrowing means losing $1 - m^*$ liquidity through foregone sales, so to obtain one more unit of liquidity, borrowing must increase by $1/m^*$. This imposes $(1+r_{\mathcal{R}})/m^*$ repayment cost and saves $1/m^*$ on securities used as collateral rather than sold.

Proposition 5 *The optimal secured lending policy induces a unique and symmetric equilibrium that is interior across a range of model specifications. If optimal secured and unsecured lending policies induce the same interior liquidity risk $0 < S^* < l$, the secured lending policy charges a lower interest rate.*

Proof. See Appendix.

Corollary 6 *For secured and unsecured lending policies that induce the same liquidity risk S^*, securities market illiquidity is higher under the unsecured policy for all $b > \bar{b}_i$ (and equal otherwise).*

Proof. Given s, when $b > \bar{b}_i$, each bank sells s_i securities under the unsecured lending policy and $s_{mi} < s_i$ securities under the secured lending policy. ■

The marginal cost of s_i given liquidity deficiency is $r_{\mathcal{R}}$, being the net cost of the extra unit of borrowing that raising s_i by one unit necessitates. In comparison, the marginal cost of s_i given liquidity deficiency under unsecured lending is $m^*(1 + r_{\mathcal{U}})$, being the loss from selling the security m^* and the net cost $m^* r_{\mathcal{U}}$ of the borrowing required to cover the remaining liquidity shortage. With $r_{\mathcal{R}} = r_{\mathcal{U}}$, these marginal costs would be equal if covering a liquidity need by only borrowing cost the same as by selling some securities and borrowing only the remainder; in other words, if the collateral constraint $s_{ri} \leq s_i - s_{mi}$ was just binding at the optimal choice of s_{mi}. Penalty rates, however, imply that the cost of borrowing is higher than that of selling, so the secured lending policy imposes a higher cost of liquidity deficiency for any given interest rate.

Proposition 7 *If the optimal unsecured lending policy induces S^* low enough that it can be induced by a secured lending policy, then the authority can achieve a higher objective W under the secured lending policy than under the unsecured lending policy.*

Proof. See Appendix.

Proposition 7 states that, when secured and unsecured lending policies are comparable, the optimal secured lending policy can achieve lower liquidity risk and higher bank profit than the optimal unsecured lending policy. Under the secured lending policy, the mitigated market illiquidity means banks make smaller losses on the securities they do sell. Importantly, this advantage does not raise incentives to hold securities, because banks with lower securities holdings benefit more from the reduced market illiquidity. That is, as explained earlier in this section, securities selling given liquidity deficiency is not increasing in s_i. The benefit of reduced market illiquidity therefore does not offset the disincentives for liquidity exposures generated by the borrowing costs.

Another implication of the results in this section is that, relative to unsecured lending, secured lending has two opposing effects on how much balance-sheet the authority uses. Holding s constant, banks borrow more from the authority under secured lending because they raise less liquidity from securities sales. Still, Proposition 5 indicates that banks are likely to hold fewer securities ex ante, which lowers their expected liquidity needs. While it is not clear which effect is larger, it is clear that gauging a policy ex-post by how much balance sheet it has used could be misleading. That is, another policy could save banks and use less balance sheet, but it may generate incentives that necessitate larger interventions in the next crisis. Furthermore, balance-sheet use is arguably an indirect measure of how much risk the authority takes with public funds, so it is also important to consider how much collateral the authority has backing its assets.

1.3.3 Securities purchase

The authority can also ensure that the liquidity value of banks' portfolios remains sufficiently high by supporting the securities price through purchases. Here the policy parameter is a purchase schedule $m^{\mathcal{S}}(b)$ such that if without intervention the market illiquidity m^* would be above $m^{\mathcal{S}}(b)$, the authority purchases enough securities to ensure the market price is $1 - m^{\mathcal{S}}(b)$.

In contrast to the other interventions analysed so far, the authority saves banks indirectly, through the securities market, and so cannot condition the quantity of liquidity it provides on individual banks' needs. The authority must therefore set the purchase schedule $m^{\mathcal{S}}(b)$ to target some $\overline{s}$ (a scalar) such that any bank with $s_i \leq \overline{s}$ is saved by the policy. Specifically, for $\overline{s}$ high enough that no bank fails,

$$m^{\mathcal{S}}(b) = \frac{l-b}{\overline{s}}, \tag{1.13}$$

and the authority intervenes at all $b > \underline{b}$ such that

$$\underline{b} = l - \overline{s} m^*(\underline{b}, s_{-i}). \tag{1.14}$$

Bank i's payoff is

$$\begin{aligned}\Pi_i^{\mathcal{S}}(s_i, s_{-i}) =& (1-\lambda)(l + s_i r_s) \\ &+ \lambda \left[\int_0^{\underline{b}} \frac{l^1(b, s_i, s_{-i})}{1 - m^*(b, s_{-i})} f(b)db + \int_{\underline{b}}^{l} \frac{l - b - s_i \frac{l-b}{\overline{s}}}{1 - \frac{l-b}{\overline{s}}} f(b)db \right].\end{aligned} \tag{1.15}$$

Proposition 8 *If the authority announces a purchase schedule $m^{\mathcal{S}}(b)$ that targets a level of liquidity risk $\overline{s}$ below that of any optimal unsecured lending policy, then in equilibrium banks choose $S > \overline{s}$ and at date 1 the authority deviates from its announced schedule.*

Proof. See Appendix.

If $\overline{s}$ is too low – e.g. not above an optimal unsecured lending policy equilibrium – banks with $s_i \leq \overline{s}$ can raise expected profits by increasing s_i, knowing that if $s_i > \overline{s}$ then the authority will at date 1 shift its schedule $m^{\mathcal{S}}(b)$ to accommodate them. The policy therefore rewards banks for taking higher liquidity exposures, having the opposite effect of penalty rates in lending policies. An attempt to induce lower securities holdings by reducing $\overline{s}$ is not credible, i.e. such a policy is time inconsistent.

For Proposition 8 to hold, it is not necessary that the authority saves all banks. As an alternative to preference 1 (defined in section 1.2.4), define preference 1a:

1a. Providing just enough liquidity to prevent any bank with $s_i \leq S$ from failing.

Preference 1a represents on objective of preventing the majority of banks from failing, rather than each individual bank.

Corollary 9 *Proposition 8 is maintained when the authority only prevents the majority of banks failing (preference 1a), provided that banks' payoff given failure depends on nothing other than s_i, m^* and b.*

Proof. See the proof of Proposition 8. ■

Corollary 9 does not require specification of a bank's payoff given failure other than assuming it does not depend in complicated ways on other agents' behaviour. If failure is sufficiently costly for banks, nash equilibria can exist at $S < S^*_{\mathcal{U}}$, with banks each choosing $s_i = \overline{s}$ to avoid risk of failure. However, these equilibria are time inconsistent, because if banks collectively raise s, the authority would respond by deviating from its announced schedule. Time consistent equilibria exist at higher S, so in this case banks' liquidity risk choices are strategic complements, as in Farhi and Tirole (2012).

Lending policies do not suffer from time inconsistency because penalty rates, paid at date 2, do not undermine the authority's primary objective of preventing bank failures in the peak of the crisis. The authority is not, however, willing to lower banks' date 1 income at the cost of bank failures, so the securities purchase policy is likely to induce a suboptimally high crisis probability. This corresponds to the case in Farhi and Tirole (2012), whereby once banks take excessive liquidity risk, the benefit to the authority of a bailout exceeds the cost. To sum up this paper's counterargument, the cost to the authority of imposing losses on banks is much higher in the midst of a liquidity crisis than once the liquidity distress subsides, so policies that penalise banks after the stress period are more credible than policies that impose costs on banks during the crisis.

1.4 Further applications and extensions

1.4.1 Capital injection policies and policy combinations

To meaningfully analyse a capital injection policy, assume that at date 0, bank i is endowed with long-term illiquid assets that cannot be liquidated at date 0 or date 1, and at date 2 are worth $a_i \geq 0$, where a_i can vary across i. Heterogeneity in long-term assets makes solving equilibria complicated but intuition can be drawn by considering bank i's optimal choice s_i when holding other banks' choices s_{-i} fixed.[6]

At date 0, the authority provides bank i the liquidity it needs to avoid failure in return for a share ϕ of bank i's date 2 payoff. Assume that $\phi(0) = 0$, $\phi < 1$, $\phi' \geq 0$, $\phi'(0) = 0$ and $\phi'' > 0$. That is, ϕ is increasing and strictly convex, flat at zero when no funds are provided, and always below one. Bank i's payoff function

[6] Heterogeneity of s_i across i means that the effect of s_{-i} on m^* cannot be captured by a sufficient statistic.

is

$$\Pi_i^{\mathcal{C}}(s_i) = (1-\lambda)(a_i + l + s_i r_s) + \lambda\left[\int_0^{\bar{b}(s_i)} \left(a_i + \frac{l^1(b,s_i)}{1-m^*(b)}\right) f(b)db + \int_{\bar{b}(s_i)}^{l} [1-\phi(-l^1(b,s_i))]a_i f(b)db\right]. \tag{1.16}$$

Proposition 10 *If interior, optimal securities holdings s_i are strictly decreasing in long-term assets a_i.*

Proof. The ex-post marginal return to securities for given $b > \bar{b}_i$ is $-m^*\phi' a_i$ which is decreasing in a_i. ■

Corollary 11 *The capital injection policy cannot leave a bank with a negative date 2 payoff whereas lending policies can.*

Proof. ϕ is less than one by assumption so every component of $\Pi_i^{\mathcal{C}}$ is nonnegative. Under either lending policy, bank i's ex-post payoff is negative if $a_i = 0$ and $b > \bar{b}_i$. ■

Proposition 10 and Corollary 11 demonstrate that for banks with low capital, a capital-injection policy has little capacity to penalise excessive liquidity-risk taking, and for the same reason, it leaves fewer of these banks ex-post insolvent. If the authority cares only about failures *during* the crisis, for instance to prevent systemic contagion, then Corollary 11 may have little relevance. Previous work on gambling for resurrection suggests that insolvency of a low-profitability bank could in fact be desirable, since these banks tend to take excessive risks; for some discussion see Freixas and Rochet (2008) chapter 9, and for some empirical evidence see Jiménez et al. (2014).

Alternatively, if banks' date 2 profits were to determine the likelihood of a further withdrawal of liquidity, as argued by for example Rochet and Vives (2004), Corollary 11 indicates a capital injection may have the benefit of staving off a further run. He and Krishnamurthy (2013) make a similar argument, showing that a capital injection can have the secondary benefit of improving banks' access to credit.

To acknowledge this potential benefit, the model is now generalised to permit the authority to combine the capital injection policy with either an optimal unsecured lending policy or an optimal secured lending policy. Denote these policies $\mathcal{CU}$ and $\mathcal{CR}$. Allow bank i to choose at date 1 how much of its liquidity deficit is funded by each policy, defining the quantity of liquidity received through capital injection as q_1 such that $0 \leq q_1 \leq -l^1(b, s_i)$. Denote the price of liquidity under the lending policies as $p_{\mathcal{P}}$ so

$$p_{\mathcal{U}} = 1 + r_{\mathcal{U}}$$

and

$$p_{\mathcal{R}} = \frac{r_{\mathcal{R}}}{m^*(b)}.$$

Bank i's payoff is

$$\Pi_i^{\mathcal{CP}}(s_i) = (1-\lambda)(a_i + l + s_i r_s) + \lambda \Bigg[\int_0^{\bar{b}(s_i)} \left(a_i + \frac{l^1(b, s_i)}{1 - m^*(b)} \right) f(b) db + \int_{\bar{b}(s_i)}^{l} \Big([1 - \phi(q_1)] a_i - p_{\mathcal{P}}(-l^1(b, s_i) - q_1) \Big) f(b) db \Bigg]. \tag{1.17}$$

First observe that if $q_1 = -l^1$, i.e. no liquidity is taken from the lending policy, the ex-post payoff is positive, so banks' chosen combination will never involve a negative ex-post payoff. Bank i will allocate liquidity across policies to equate their marginal costs, so the optimal choice of q_1 is

$$\max \left\{ \frac{\phi'^{-1}(p_{\mathcal{P}})}{a_i}, -l^1 \right\}$$

where ϕ'^{-1} is strictly decreasing. Intuitively, more liquidity will be taken from the capital injection policy when the interest rate on lending is higher, and when the bank will have less capital to repay at date 2. An implication is that banks that under lending policies would be most likely to be insolvent at date 2 are those that will rely most heavily on the capital injection. Like the capital injection policy without any lending, the combined policies make the risk of illiquidity costlier for banks with better post-crisis prospects than for others.

For liquidity withdrawals slightly above $\bar{b}_i$, banks will utilise only the capital injection policy, but for larger withdrawals, given a sufficiently high a_i they will maintain a substantial claim on their long-term assets and rely more on the lending policy. When the lending policy is used at all, its use will increase one for one with the size of the liquidity deficit; i.e. it will be used at the margin (of b or s_i).

This indicates that the results in section 1.3 for unsecured and secured lending policies would carry over to a combination of capital injection and lending policies. For banks that utilise the lending component of the combination, a higher liquidity deficit implies more use of the lending policy, so holding the interest rate constant, a $\mathcal{CR}$ policy is more deterring to liquidity risk taking than a $\mathcal{CU}$ policy. For the same reason, the former would induce more take-up of the capital injection policy, although market illiquidity would still be higher under the $\mathcal{CU}$ policy, because liquidity-deficit banks always liquidate all their securities. The lower m^* under the $\mathcal{CR}$ policy has a positive effect on banks' date 2 payoffs, without incentivising more liquidity risk taking, so the $\mathcal{CR}$ policy can be expected to bring higher welfare than the $\mathcal{CU}$ policy.

1.4.2 Positive haircuts on secured lending

Section 1.3.2 assumes that the authority requires no haircut on secured lending, which covers it against all principal risk because the value of securities recovers at date 2. This section discusses positive haircuts and argues that they are unlikely to weaken the conclusions.

Haircuts h are defined in section 1.3.2 such that one security can be used as collateral to borrow $1-h$ funds. For the liquidity injection to be capable of saving banks, a security used as collateral must bring sufficiently more liquidity than selling it; specifically, the haircut must satisfy $h \leq (l-b)/s_i$. The maximum h is decreasing in the size of the liquidity withdrawal b because each bank's need for liquidity is increasing in the size of the withdrawal. Indeed, during the 2008 liquidity crisis many central banks extended the range of securities they would accept as collateral, which was a reduction of haircuts on the newly accepted securities from 100 per cent.

When h can be positive Lemma 4 does not in general hold, but as in section 1.4.1, it is informative to look at individual banks' payoff functions. Conditional on being liquidity deficient, bank i's binding liquidity constraint is

$$c_i + s_{ri}(1-h) + s_{mi}(1-m^*) \geq b$$

and so the quantity of securities used as collateral is

$$s_{ri} = \frac{s_i m^* + b - l}{m^* - h}$$

and the quantity of securities sold is

$$s_{mi} = s_i - s_{ri} = \frac{l - b - s_i h}{m^* - h}.$$

Securities sales given liquidity deficiency s_{mi} is here decreasing in s_i, whereas in section 1.3.2 it is independent of s_i. A positive haircut means that if one more security is held, it cannot collateralise enough borrowing to cover the forgone unit of cash, so holding more securities requires posting disproportionately more as collateral, and therefore selling less. Given s and b, higher haircuts therefore reduce m^*.

If bank i is liquidity deficient, its ex-post payoff is the negative of its liquidity shortfall $b - c_i - (s_i - s_{ri})(1 - m^*)$ multiplied by $1 + r_{\mathcal{R}}$, plus the date 2 value of its securities not sold s_{ri}. The corresponding ex-post marginal return to securities is

$$-\frac{m^*[r_{\mathcal{R}}(1-h)-h]}{m^*-h}.$$

This marginal return is *negatively* related to the market price $1 - m^*$, because holding more securities entails less selling. Accordingly, if positive haircuts reduce market illiquidity, they are also likely to reduce the marginal return to securities and incentivise lower ex-ante liquidity exposures. Further, since the ex-post payoff is decreasing in market illiquidity, another likely outcome is higher ex-post payoffs.

1.4.3 Heterogeneous liquidity positions and an interbank market

The policies in section 1.3 entail no interbank transactions in equilibrium, because banks optimally hold symmetric securities positions and then experience the same liquidity withdrawal. If instead some banks were to hold excess spare cash in case a liquidity withdrawal occurs, interbank transactions would take place in equilibrium. This section presents a simple modification to the model in section 1.2 such that interbank transactions occur in equilibrium and shows that the previous results are maintained.

Assume that a proportion δ of *highly liquid* banks expect securities to pay $r_s = 0$ when there is no liquidity withdrawal, and aside from this the model is as described in section 1.2. Highly liquid banks have no reason to hold securities at date 0, but if a liquidity withdrawal occurs at date 1 and $m^* > 0$ then they can profitably purchase securities from banks that are selling them. These purchases can also be interpreted as interbank repos, similar to Freixas and Holthausen (2004) and Allen et al. (2009).

Proposition 12 *When δ banks are highly liquid, date 1 interbank transactions occur in equilibrium in some states of the world, and the formal results in sections 1.3.1 to 1.3.3 are maintained with respect to the other $1 - \delta$ banks.*

Proof. See Appendix.

With or without highly liquid banks, those with insufficient cash are influenced by others only through the others' effect on m^*, that is, through their contribution to the banking system's liquidity position and thus the market return on liquidity. Accordingly, to a distressed bank, the distribution of liquidity needs across other banks does not matter. Heterogeneous liquidity positions only affect the results in section 1.3 to the extent that the aggregate liquidity exposure of the banking system changes.

1.5 Conclusion

This paper analyses four liquidity-injection policy frameworks that can save banks from failure during a liquidity crisis: lending to banks unsecured or, similarly, guaranteeing banks' newly issued unsecured debt; lending to banks against securities as collateral; buying securities that banks hold to raise the securities' market price; or injecting capital into distressed banks. The liquidity crisis is modelled as a system-wide withdrawal of funding liquidity that leads banks to heavily sell securities, resulting in securities price depression to the point that banks cannot survive the withdrawal. Banks' pre-crisis exposures to securities with liquidity risk determine how large the outflow must be to cause bank failures, and hence the likelihood of a crisis occurring.

The model demonstrates several novel and important characteristics of the four policy frameworks. A secured lending policy can charge high enough interest rates to penalise and thus deter banks from holding excessive securities with liquidity risk, while also curtailing price depression in securities markets, because distressed banks must provide securities as collateral rather than selling them. Since the benefit to a bank of this price effect depends on the quantity of securities it sells, and a less liquid bank is more constrained in its selling because it must collateralise more borrowing, the curtailed price depression, while reducing losses for banks in general, does not strengthen incentives for liquidity risk taking. Alternatively, in an unsecured policy, penalising interest rates lead banks to fire sell their securities and only borrow from the authority their remaining liquidity needs. Relative to a secured lending policy, this results in a lower securities market price and higher losses for banks, without better deterring liquidity risk taking.

Under a securities purchase policy, the authority may be able to induce a low-risk equilibrium by ex-ante stating that it will only provide limited price support during a crisis, but, in line with Farhi and Tirole (2012), if banks nonetheless coordinate on a high risk level, the authority must then deviate from its ex-ante statement to prevent a banking crisis. The low-exposure equilibrium is therefore not credible. In contrast, the lending policies can credibly charge penalising rates if banks are not required to repay until their securities and longer-term assets can be liquidated at reasonable prices. Under a capital injection policy, banks with less capital ex-ante have lower post-crisis repayments, and are thus less deterred from taking liquidity risk but also less likely to be insolvent post crisis.

In late 2008 the most heavily relied upon liquidity injection policies were secured lending and government guarantees on banks' unsecured debt. US authorities relied more and earlier on expanding secured lending than European authorities; European authorities' guarantees on banks' unsecured debt were larger than and roughly simultaneous with their secured lending expansions.[7] These results suggest a novel reason that could have contributed to the difference in policy decisions – US authorities may have been dealing with heavier fire selling than in Europe. For example, over a period in late 2008 the S&P index on US investment-grade corporate bonds fell around 15 per cent, whereas the largest fall in the corresponding index for European bonds was around 5 per cent (and, consistent with fire sale dynamics, both falls subsequently reversed).

Several other features of the model are worth relating to interventions during the 2008 liquidity crisis:

- Emergency lending policies typically charged a premium above pre-crisis market rates, but the model suggests this may not be high enough to deter liquidity risk taking. Specifically, to be penalising, the rate charged should be higher than what non-distressed banks pay in private markets during the crisis, which is what a distressed bank would be paying if it had taken less risk. As discussed in section 1.3.1, this also aligns with Bagehot (1873)'s suggestion.

- The model emphasises that emergency loans should be long enough for banks to hold off repayment until liquidity conditions improve, so that the authority need not offer banks terms so favourable they can satisfy them while liquidity constrained. In both the US and Europe banks could utilise guarantees on debt maturing several years later, and the introduced secured lending programs offered extended maturities.

- Section 1.4.2 argues that to prevent failures, the authority's haircuts on secured lending should permit banks to acquire more funds than by selling the

[7] More detail is provided in Appendix 1.6.1.

collateral. Indeed, Cechetti (2009) writes “the Fed is taking collateral at a price that is almost surely above its market price” (page 67).

- By relying heavily on secured lending policies, authorities may have expanded their balance sheets more than if they did not require collateral, because banks cannot sell securities they pledge and therefore likely borrow more. Still, the model suggests that secured lending may better deter liquidity risk taking, potentially reducing the severity and need for intervention in future crises. Moreover, the authority arguably takes less balance-sheet risk than under an uncollateralised lending policy.

1.6 Appendix

1.6.1 Liquidity injection policies in the US and Europe

This appendix reviews some of the largest liquidity injection policies adopted by authorities in Europe and the US around late 2008. Both regions utilised secured lending, capital injections, and unsecured lending subsidisation. Unsecured lending subsidisation was mostly through government guarantees on banks' unsecured debt, with also some direct loans to banks. The US relied most heavily on secured lending; in Europe, government guarantees on banks' unsecured debt were more prominent.

ECB increased secured lending by modifying and expanding its standard tools for open market operations. These are the main refinancing operations (MRO) and longer-term refinancing operations (LTRO), under which banks borrow from ECB against eligible collateral. MROs are conducted weekly with one-week maturity and LTROs are typically conducted monthly with maturities of one month and longer. In March 2008, ECB announced it would run a series of LTROs with six-month maturities, compared to maturities of three months in previous LTROs. Prior to October 2008, ECB priced the MROs and LTROs by taking bids from banks comprising interest rates and corresponding quantities, auctioning a predetermined total amount at the lowest successful interest-rate bid; the amount auctioned was calibrated to leave the outcome interest rate a certain level above the 'deposit rate' that ECB pays banks on their overnight cash holdings. On 15 October for MROs and 30 October for LTROs, ECB switched to a fixed rate tender with full allotment, whereby it fixed the interest rate and banks could borrow any amount requested. On 23 October ECB also substantially widened the range of eligible collateral, accepting more corporate debt instruments and lowering the required credit rating of collateral from A- to BBB-. The most rapid and substantial increase in MRO and LTRO lending occurred between late September and late October 2008, rising from 480 billion to 820 billion EUR. Over the same period the interest rate on ECB's lending declined from around 4.7 to 3.75 per cent, above the interbank EONIA rate which declined from 3.70 to 3.55 per cent.

In mid October several European countries offered government guarantees on banks' newly issued debt, guaranteeing around 770 billion EUR, and often charging prices estimated to be close to market rates in normal times.[8] Around the same time, some of these countries engaged in bank recapitalisation schemes,

[8] The 770 billion EUR figure multiplies 5.7 per cent of Euro area GDP (provided in Table 2 of Attinasi (2010)) by 2009 Euro area GDP of 12.9 trillion EUR. It excludes guarantees placed in 2009.

with a combined cap of 140 billion EUR, and purchased or guaranteed around 43 billion EUR of banks' assets.[9] A large component of this was the Swiss National Bank's (SNB) transaction with UBS, under which SNB created a 'bad bank' fund, owned and mostly funded by SNB, that purchased around 30 billion EUR of assets from UBS with an arrangement that SNB would receive UBS shares if the bad bank eventually made a loss. The transaction therefore had similarities to an equity purchase. In November 2013 SNB sold the last of the fund back to UBS and announced that it made around 2.8 billion EUR capital gains on top of interest payments.

Throughout the crisis the US Federal Reserve introduced a number of new facilities for collateralised open market operations, including the term auction facility (TAF), the primary dealer credit facility (PDCF) and the term securities lending facility (TSLF).[10] The TAF, introduced in March 2007, lent to a wide range of depository institutions – in contrast to the standard open market operations that only transact with the 20 or so primary dealers – for terms of one or three months, via single price auctions each of a fixed total amount. The largest monthly increase in TAF lending was from 125 to 390 billion USD between early October and early November 2008. The PDCF, introduced in March 2008, lent funds without limit to primary dealers on an overnight basis, at the Fed's overnight policy rate and with an additional frequency-based fee for each loan to a borrower that had used the facility more than 45 times. The TSLF, also introduced in March 2008, made one-month loans of Treasury securities to primary dealers, collateralised by other securities, through single price auctions. In mid September 2008 the Fed widened its acceptable collateral for the PDCF – from investment-grade securities to those typically accepted in private repo markets – and the TSLF – from certain types of AAA securities to any investment-grade debt instruments. From mid September to early October TSLF loans outstanding rose from 135 billion to 275 billion USD, and overnight lending under the PDCF rose from zero to 155 billion USD.

US authorities also injected substantial liquidity using unsecured-debt subsidisation and capital injections. On 7 October 2008 the Fed introduced the commercial paper funding facility (CPFF) to purchase newly issued commercial paper of three-month maturity from a wide variety of companies, with a substantial proportion from the banking sector. It purchased unsecured commercial paper (essentially making unsecured loans), charging the overnight index swap rate (OIS)

[9]These figures are from Attinasi (2010) and Panetta et al. (2009).

[10]Some facilities not discussed are: the term asset-backed securities loan facility (TALF) and the large scale asset purchases (LSAP), aimed at stimulating lending to borrowers outside the financial system; and the money market investor funding facility (MMIFF), targeted at liquidity problems in the money market fund sector.

plus 100 basis points, and asset-backed commercial paper (ABCP), charging OIS plus 300 basis points. By the end of October the Fed owned 157 billion USD of unsecured commercial paper and 94 billion of ABCP.[11] On 14 October 2008 the Federal Deposit Insurance Corporation (FDIC) implemented the temporary liquidity guarantee program (TLGP), which guaranteed without limit banks' newly issued unsecured debt, charging a 75 basis point fee for any loan that applied the guarantee. TLGP-guaranteed debt outstanding reached 224 billion by the end of 2008, later peaking at 336 billion USD.

Capital injections in the US were made under the Troubled Assets Relief Program (TARP). The largest part of TARP was the Capital Purchase Program (CPP), through which on 28 October 2008 the US Treasury purchased 115 billion USD of equity and warrants from eight of the largest US banks, and by February 2009 had disbursed a total of 194 billion USD to 317 different financial entities. Additional TARP funds were spent on institution-specific purchases, providing AIG 40 billion on 10 November 2008 – which it used to partially repay a senior unsecured loan of 85 billion USD from the Fed made on 15 September – and providing Bank of America 20 billion on 16 January. The US treasury made positive returns on the CPP and both institution-specific purchases.

1.6.2 Proofs

Definition *Throughout these proofs, $\hat{d}f(x)/\hat{d}x$ and $\hat{\partial}f(x)/\hat{\partial}x$ refer to generalised derivatives, defined, as in Clarke (1975), as the convex hull of the set of limits of the form $df(x+h_i)/dx$ and $\partial f(x+h_i)/\partial x$ where $h_i \to 0$ as $i \to \infty$. In any neighbourhood such that f is continuously differentiable, the generalised derivative collapses to the standard derivative.*

Remark *In most cases throughout these proofs, Π_i is a function of the almost everywhere continuously differentiable functions m^* and $\overline{b}$. In such cases the generalised derivatives of Π_i with respect to s_i or S are equal to the interval in $\mathbb{R}$ between the lefthand and righthand derivatives*

$$\lim_{h\to 0^-} \frac{f(x+h)-f(x)}{h} \quad \text{and} \quad \lim_{h\to 0^+} \frac{f(x+h)-f(x)}{h}.$$

Proof of Lemma 1. Consider three function properties: (a) unique and Lipschitz continuous; (b) nondecreasing; and (c) almost everywhere continuously differentiable. Sufficient for Lemma 1 is that: $m^*(b, s_{-i})$ has properties (a), (b) and (c) with respect to b and, if $s_{-i} = S$, to S; and $\overline{b}(s_i, s_{-i})$ has properties (a) and (c)

[11] The figure provided in the introduction assumes that half of the CPFF funds went to banks.

with respect to s_i and, if $s_{-i} = S$, to S, and property (b2): decreasing in s_i and, when $s_i > 0$, in S. This proof will make reference to these properties.

Recall that $m^*(b, s_{-i})$ is defined implicitly by

$$L_S(m^*) - L_D(m^*, b, s) = 0 \tag{1.18}$$

where the definition of L_S is provided in section 1.2.2, and L_D is defined as

$$L_D = \int_0^1 L_i di + \gamma b. \tag{1.19}$$

The unsecured lending policy is characterised by

$$L_i(m, b, s_i) = \begin{cases} b + s_i - l & \text{if } b \leq l - s_i m \\ s_i(1 - m) & \text{if } b > l - s_i m. \end{cases} \tag{1.20}$$

Examples of some of the functions in this proof are provided in figures 1.1 and 1.3.

First, m^* is shown to be zero if and only if b and S are not greater than certain thresholds, implying that properties (a), (b) and (c) hold for b and S below these thresholds. Then the properties are each demonstrated separately for the remaining values of b and S, making use of the fact that $m^* > 0$.

Define $\underline{m} > 0$ such that $s_i\underline{m}(1 + \gamma) + L_S(\underline{m}) = \gamma l$. If $0 \leq m^* < \underline{m}$ then

$$l - s_i m^* > \frac{l + L_S(m^*)}{1 + \gamma} \geq b,$$

where the first inequality is true by the definition of $\underline{m}$ and the second because selling by external creditors ensures $L_S(m^*) \geq b(1 + \gamma) - l$. Therefore if m^* is in a small enough neighbourhood of zero then $L_i = b + s_i - l$ for all i, so $L_D = b(1 + \gamma) + S - l$ which is increasing and continuous in b. Further, $m^* = 0 \Leftrightarrow L_D \leq 0$ by the definition of L_S. Accordingly, $m^* = 0$ if and only if $b \leq \hat{b}(s) \equiv (l - S)/(1 + \gamma)$. The condition $b \leq \hat{b}(s)$ can be equivalently stated as $S \leq \hat{b}^{-1}(b)$.

Property (a) of m^*: Consider $b > \hat{b}(s)$, which implies $m^* > 0$ and in turn that L'_S is continuous and positive for m in some neighbourhood of m^*. Since L_i is Lipschitz continuous in m, b and s_i, and nondecreasing in m, L_D is Lipschitz continuous in m, b and, if $s_{-i} = S$, in S, and nondecreasing in m, by expressions 1.19 and 1.20. Therefore, for m in some neighbourhood of m^*, the expression $L_S(m) - L_D(m, b, s)$ is strictly increasing in m and Lipschitz continuous in all variables. Accordingly, the Lipschitz implicit function theorem (such as in Clarke (1990)) implies that when positive, market illiquidity $m^*(b, s_{-i})$ is Lipschitz continuous and unique in b, and if $s_{-i} = S$, in S.

Furthermore, if $b = \hat{b}(s)$, or equivalently $S = \hat{b}^{-1}(b)$, then $L_D = b(1+\gamma) + S - l$ so m^* is continuous with bounded gradient by the definition of L_S and equation 1.18. Therefore property (a) holds.

Property (b) of m^*: As just shown, $L_S(m) - L_D(m, b, s)$ is nondecreasing in m and nonincreasing in b and, if $s_{-i} = S$, nonincreasing in S. Therefore m^* defined by $L_S(m^*) - L_D(m^*, b, s) = 0$ is nondecreasing in b and, if $s_{-i} = S$, in S.

Property (c) of m^*: Fix s. Define $\mathcal{S}_0 \subseteq s$ such that $s_0 \in \mathcal{S}_0$ if and only if the measure of banks that each hold $s_i = s_0$ is positive. For example, if $s_{-i} = \{S\}$ then $\mathcal{S}_0 = S$. The measure of $\mathcal{S}_0$ is zero because the set of banks has finite measure one. Expressions 1.19 and 1.20 imply that $\partial L_D / \partial m$ and $\partial L_D / \partial b$ are defined and continuous except in the set $\{(m, b) | (l - b)/m \in \mathcal{S}_0\}$, which is the (m, b) at which a positive measure of banks are at $b = l - s_i m$. Therefore $L_S(m) - L_D(m, b)$ is continuously differentiable in any open subset of $\{(m, b) | (l - b)/m \notin \mathcal{S}_0, m > 0\}$, and from the proof of property (a), increasing in m. The implicit function theorem then implies $m^*(b)$ is continuously differentiable for any b in $\{b | (l - b)/m^*(b) \notin \mathcal{S}_0, m^*(b) > 0\}$. Property (b) shows that $m^*(b)$ is nondecreasing in b, so for any s_0 there is a unique b satisfying $b = l - s_0 m^*(b)$. Therefore, the set of b such that $(l - b)/m^*(b) \in \mathcal{S}_0$ has measure zero because $\mathcal{S}_0$ has measure zero. In turn, $m^*(b)$ is almost everywhere continuously differentiable.

Now fix b and assume $s_{-i} = S$. The aforementioned logic also applies for $m^*(S)$. That is, $\partial L_D / \partial S$ is continuous except on the set $\{(m, S) | Sm = l - b\}$. By the implicit function theorem $m^*(S)$ is therefore continuously differentiable on $\{S | Sm^*(S) \neq (l - b), m^*(S) > 0\}$, which, for $S > \hat{b}^{-1}(b)$, excludes only a unique value of S because $m^*(S)$ is nondecreasing in S from property (b).

Now consider $\overline{b}(s_i, s_{-i})$, defined implicitly by $g = 0$ where

$$g(b, s_i, s_{-i}) \equiv b - l + s_i m^*(b, s_{-i}). \tag{1.21}$$

Property (a) of $\overline{b}_i$: This follows from the Lipschitz implicit function theorem and the properties of m^*, because: i) Lipschitz continuity of m^* implies Lipschitz continuity of g; and ii) m^* being nondecreasing in b implies g is strictly increasing in b.

Property (b2) of $\overline{b}_i$: Note that $g = 0$ implies $m^* > 0$ because $b = l$ implies

$m^*(b, s_{-i}) = m^*(l, s_{-i}) \geq M(\gamma l) > 0$. Positive m^* implies g is strictly increasing in s_i. Also, if $s_{-i} = S$ and $m^* > 0$ then m^* is strictly increasing in S, because $m > 0$ implies $L_S(m) - L_D(m, b, S)$ is strictly decreasing in S. Therefore, if $s_{-i} = S$ and $s_i > 0$ then g is strictly increasing in S.

Property (c) of $\bar{b}_i$: From expression 1.21, g is continuously differentiable at all b such that m^* is continuously differentiable. Property (a) of m^* shows that $\hat{d}m^*/\hat{d}b \geq 0$, therefore $\hat{d}g/\hat{d}b > 0$. Almost everywhere continuous differentiability of g in s_i, and, if $s_{-i} = S$, in S, then follows from property (c) of m^*, by the implicit function theorem. ■

Proof of Proposition 3. This proof has three parts. Part 1 shows that $r_{\mathcal{U}} \geq r_{pen}$ implies $d\Pi_i^{\mathcal{U}}/ds_i$ is continuous and strictly decreasing in s_i, and homogeneous across i, therefore there are no asymmetric equilibria. Accordingly, without loss of generality part 2 sets $s_{-i} = S$ and shows that $r_{\mathcal{U}} \geq r_{pen}$ implies $d\Pi_i^{\mathcal{U}}/ds_i$ is continuous and strictly decreasing in S. Combined with strict concavity of $\Pi_i^{\mathcal{U}}$ from part 1, this means $s_i^*(S)$ is continuously decreasing in S so there is a unique equilibrium characterised by $0 \leq s_i^*(S^*) = S^* \leq l$. Part 3 provides conditions for an interior S^*.

Part 1.

The liquidity-withdrawal threshold $\bar{b}_i$ is Lipschitz continuous in s_i by Lemma 1, so by equality of the two integrands in expression 1.9 at $b = \bar{b}_i$,

$$\frac{d\Pi_i^{\mathcal{U}}(s_i, s_{-i})}{ds_i} = (1-\lambda)r_s + \lambda\Bigg[\int_0^{\bar{b}(s_i,s_{-i})} \frac{-m^*(b, s_{-i})}{1-m^*(b, s_{-i})} f(b)db + \int_{\bar{b}(s_i,s_{-i})}^{l} -m^*(b, s_{-i})(1+r_{\mathcal{U}})f(b)db\Bigg]. \tag{1.22}$$

By Lemma 1 expression 1.22 is continuous in s_i and, if $s_{-i} = S$, in S. Furthermore,

$$\frac{\hat{d}^2\Pi_i^{\mathcal{U}}(s_i, s_{-i})}{\hat{d}s_i^2} = \lambda\frac{\hat{d}\bar{b}(s_i, s_{-i})}{\hat{d}s_i} m^*(\bar{b}_i, s_{-i})\left(1 + r_{\mathcal{U}} - \frac{1}{1-m^*(\bar{b}_i, s_{-i})}\right) f(\bar{b}_i). \tag{1.23}$$

Property (b2) of $\bar{b}_i$ in Lemma 1 shows that $m^*(\bar{b}, s_{-i}) > 0$ and $\hat{d}\bar{b}_i/\hat{d}s_i < 0$. Because $M(l+\gamma l) > m^*(\bar{b}_i, s_{-i})$, $r_{\mathcal{U}} \geq r_{pen}$ implies that the term in large parentheses in expression 1.23 is positive. Expression 1.23 is then negative by positivity of λ and f.

Part 2.

Given $s_{-i} = S$, continuity and uniqueness of m^* and $\bar{b}_i$ from Lemma 1 permit $\hat{d}^2\Pi_i^{\mathcal{U}}/\hat{d}s_i\hat{d}S$ to be expressed as

$$\frac{\hat{d}^2\Pi_i^{\mathcal{U}}(s_i,S)}{\hat{d}s_i\hat{d}S}$$
$$= \lambda\Bigg[\int_0^{\bar{b}(s_i,S)} \frac{-\frac{\hat{d}m^*(b,S)}{\hat{d}S}}{(1-m^*(b,S))^2} f(b)db + \int_{\bar{b}(s_i,S)}^{l} -\frac{\hat{d}m^*(b,S)}{\hat{d}S}(1+r_{\mathcal{U}})f(b)db$$
$$+ \frac{\hat{d}\bar{b}(s_i,S)}{\hat{d}S} m^*(\bar{b}_i,S)\left(1+r_{\mathcal{U}} - \frac{1}{1-m^*(\bar{b}_i,S)}\right) f(\bar{b}_i)\Bigg]. \tag{1.24}$$

When $s_{-i} = S$ market illiquidity takes the form in expression 1.4, increasing in S whenever $m^* > 0$ and constant in S otherwise. Therefore the sum of the integral terms in expression 1.24 is negative. By property (b2) of $\bar{b}_i$ in Lemma 1, if $s_i > 0$ then $\hat{d}\bar{b}(s_i,S)/\hat{d}S < 0$, and, from equation 1.21, if $s_i = 0$ then $\hat{d}\bar{b}(s_i,S)/\hat{d}S = 0$, so $r_{\mathcal{U}} \geq r_{pen}$ implies the last term in expression 1.24 is nonpositive. Therefore expression 1.24 is negative.

Part 3.

Define

$$\underline{r}_s \equiv \frac{\lambda}{1-\lambda}\int_{l/(1+\gamma)}^{l} \frac{M(b(1+\gamma)-l)}{1-M(b(1+\gamma)-l)} f(b)db$$

and

$$\bar{r}_s(r_{\mathcal{U}}) = \frac{\lambda}{1-\lambda}\left[\int_0^{\bar{b}(l,l)} \frac{m_G^*(b,l)}{1-m_G^*(b,l)} f(b)db + \int_{\bar{b}(l,l)}^{l} m_{\mathcal{U}}^*(b,l)(1+r_{\mathcal{U}})f(b)db\right].$$

Since $m_{\mathcal{G}}^* > M(b(1+\gamma)-l)$ and $m_{\mathcal{U}}^* > M(b(1+\gamma)-l)$ for any (b,s), clearly $\bar{r}_s(r_{\mathcal{U}}) > \underline{r}_s$. Moreover, $r_s > \underline{r}_s$ implies $d\Pi_i^{\mathcal{U}}(0,0)/ds_i > 0$ and $r_s < \bar{r}_s(r_{\mathcal{U}})$ implies $d\Pi_i^{\mathcal{U}}(l,l)/ds_i < 0$, so by continuity of $d\Pi_i^{\mathcal{U}}/ds_i$ in s_i and S, if $r_s \in (\underline{r}_s, \bar{r}_s(r_{\mathcal{U}}))$ then the equilibrium $s_i^*(S^*) = S^*$ satisfies $0 < S^* < l$. ■

Proof of Lemma 4. Consider three function properties: (a) unique and Lipschitz continuous; (b) nondecreasing; and (c) almost everywhere continuously differentiable. Sufficient for Lemma 4 is that: $m^*(b, s_{-i})$ has properties (a) and (c) with respect to b and, if $s_{-i} = S$, properties (a), (b) and (c) with respect to S; and $\overline{b}(s_i, s_{-i})$ has properties (a) and (c) with respect to s_i and, if $s_{-i} = S$, to S, and property (b2): strictly decreasing in s_i and, when $s_i > 0$, weakly decreasing in S. This proof will make reference to these properties.

Recall that $m^*(b, s_{-i})$ is defined implicitly by

$$L_S(m^*) - L_D(m^*, b, s) = 0 \tag{1.25}$$

where by definition

$$L_D = \int_0^1 L_i di + \gamma b \tag{1.26}$$

and the secured lending policy is characterised by

$$L_i(m, b, s_i) = \begin{cases} b + s_i - l & \text{if } b \leq l - s_i m \\ (l - b)(1/m - 1) & \text{if } b > l - s_i m. \end{cases} \tag{1.27}$$

The proof of Lemma 1 defines $\hat{b}$ such that $b \leq \hat{b}(s) \Leftrightarrow m^* = 0$ and $S \leq \hat{b}^{-1}(b) \Leftrightarrow m^* = 0$, and shows that m^* is Lipschitz continuous at $b = \hat{b}(s)$ and $S = \hat{b}^{-1}(b)$, and therefore that properties (a) and (c) of m^* hold at b and S up to these thresholds. The following considers $b > \hat{b}(s)$ and $S > \hat{b}^{-1}(b)$.

Property (a) of m^*: If $m > 0$ then by definition L_S is increasing and Lipschitz continuous in m. Because L_i is Lipschitz continuous in m, b and s_i and nonincreasing in m, expression 1.26 implies L_D is Lipschitz continuous in m, b and S and nonincreasing in m. Therefore, by the Lipschitz implicit function theorem, if $b > \hat{b}(s)$ or $S > \hat{b}^{-1}(b)$ then $m^*(b, s_{-i})$, defined in equation 1.25, is unique and Lipschitz continuous in b and, if $s_{-i} = S$, in S.

Property (b) of m^*: When $s_{-i} = S$,

$$L_D(m, S) = \begin{cases} b(1+\gamma) + S - l & \text{if } b \leq l - Sm \\ (l - b)(1/m - 1) + \gamma b & \text{if } b > l - Sm, \end{cases} \tag{1.28}$$

which is nondecreasing in S and nonincreasing in m. By equation 1.25, these directions imply m^* is nondecreasing in S, given that for $m^* > 0$, expression 1.25 is increasing in m.

Property (c) of m^*: For $m > 0$, the implicit function theorem implies that continuous differentiability of $m^*(b, s_{-i})$ follows from property (a) for any b such that L_D is continuously differentiable in a neighbourhood of $(m^*(b), b)$, and, if $s_{-i} = S$, for any S such that L_D is continuously differentiable in a neighbourhood of $(m^*(s_{-i}), S)$. The next part shows that the measure of b without such a neighbourhood is zero, and subsequently the same is shown for S when $s_{-i} = S$.

Denoting the total securities held by banks with $i \leq x$ as $F_s(x)$, and defining $\bar{i}(m, b) \in [0, 1]$ such that $i < \bar{i} \Rightarrow s_i < (l - b)/m$ and $i \geq \bar{i} \Rightarrow s_i \geq (l - b)/m$, observe that

$$L_D(m, b) = \int_0^{\bar{i}} (b + s_i - l) dF_s(i) + \int_{\bar{i}}^1 (l - b) \left(\frac{1}{m} - 1 \right) dF_s(i) + \gamma b. \quad (1.29)$$

Since both integrands in expression 1.29 are continuously differentiable in b and m, L_D is continuously differentiable for any b such that $F_s(\bar{i}(m^*(b), b))$ is continuous.

Fix s and define $\mathcal{S}_0 \subseteq s$ such that $s_0 \in \mathcal{S}_0$ if and only if the measure of banks that each hold $s_i = s_0$ is positive. For example, if $s_{-i} = S$ then $\mathcal{S}_0 = S$. The measure of $\mathcal{S}_0$ is necessarily zero because the set of banks has finite measure one. Discontinuities in $F_s(\bar{i})$ can only occur at b such that a positive measure of banks are at the threshold of liquidity deficiency, so L_D is continuously differentiable on $\{b | (l - b)/m^*(b) \notin \mathcal{S}_0\}$. Say there is a nondegenerate interval $[b_0, b_1]$ such that $b \in [b_0, b_1] \Rightarrow (l - b)/m^*(b) = s_0$ for some $s_0 \in \mathcal{S}_0$. The measure of banks with $s_i < (l - b)/m^*(b) = s_0$, i.e. $F_s(\bar{i})$, is constant in $[b_0, b_1]$, so L_D is continuously differentiable on (b_0, b_1). Moreover, Lipschitz continuity of $m^*(b)$ ensures that for each $s_0 \in \mathcal{S}_0$, the number of such disjoint intervals $[b_0, b_1]$ is countable. Therefore each $s_0 \in \mathcal{S}_0$ contributes a zero measure of discontinuities to $F_s(\bar{i}(m^*(b), b))$, and since $\mathcal{S}_0$ has zero measure, L_D is almost everywhere continuously differentiable.

Property (b) of $m^*(S)$ implies there is a unique S such that $Sm^*(S) = l - b$, and expression 1.28 is continuously differentiable in $(m^*(S), S)$ at all other S.

Property (a) of $\bar{b}_i$: Consider the expression

$$g_1(b, s_i, s_{-i}) \equiv b + s_i m^*(b, s_{-i}) - l \quad (1.30)$$

such that $\bar{b}(s_i, s_{-i})$ is implicitly defined by $g_1 = 0$. Lipschitz continuity of g_1 follows from Lipschitz continuity of m^*. The following shows that $\hat{d}g_1/\hat{d}b > 0$ whenever $g_1 = 0$, so $\bar{b}_i$ is unique and Lipschitz continuous by the Lipschitz implicit function theorem.

If $m^*(b)$ is differentiable then

$$\frac{dg_1}{db} = 1 + s_i \frac{dm^*}{db}. \tag{1.31}$$

Define as $\mathcal{B}_0$ the set of b such that $L_D(m^*(b), b)$ is not continuously differentiable. The proof of property (c) of m^* shows that $m^*(b)$ is continuously differentiable for all $b \notin \mathcal{B}_0$ and that $\mathcal{B}_0$ has zero measure. Therefore, using expression 1.29, if $b \notin \mathcal{B}_0$ then

$$\frac{dm^*}{db} = \frac{\frac{\partial L_D}{\partial b}}{\frac{\partial L_S}{\partial m} - \frac{\partial L_D}{\partial m}} = \frac{F_s(\bar{i}) - (1 - F_s(\bar{i}))\left(\frac{1}{m^*} - 1\right) + \gamma}{L_S'(m^*) + (1 - F_s(\bar{i}))(l - b)\frac{1}{m^{*2}}} \tag{1.32}$$

and

$$\begin{aligned} \left.\frac{dg_1}{db}\right|_{g_1=0} &= 1 + s_i \frac{F_s(\bar{i}) - (1 - F_s(\bar{i}))\left(\frac{s_i}{l-b} - 1\right) + \gamma}{L_S'(m^*) + (1 - F_s(\bar{i}))\frac{s_i^2}{l-b}} \\ &= \frac{s_i(1+\gamma) + L_S'(m^*)}{L_S'(m^*) + (1 - F_s(\bar{i}))\frac{s_i^2}{l-b}} > 0. \end{aligned} \tag{1.33}$$

Since $\mathcal{B}_0$ has zero measure, the lefthand and righthand derivatives of g_1 with respect to b exist for all $b \in (0, l)$. Further, expression 1.33 implies that at $(\bar{b}(s_i, s_{-i}), s_i, s_{-i})$, these lefthand and righthand derivatives are positive, so Lipschitz continuity of g_1 implies $\hat{d}g_1/\hat{d}b > 0$. Therefore $\bar{b}_i$ is unique and Lipschitz continuous in s_i, and, if $s_{-i} = S$, in S, by the Lipschitz implicit function theorem.

Property (b2) of $\bar{b}_i$: The result follows from g_1 being strictly increasing in s_i, strictly decreasing in S if $s_i > 0$ and $s_{-i} = S$, by property (b) of m^*, and strictly increasing in b when $g_1 = 0$.

Property (c) of $\bar{b}_i$: Expression 1.30 shows that g_1 is continuously differentiable at b such that m^* is continuously differentiable. By the proof of property (a) of $\bar{b}_i$, if $g_1 = 0$ then $\hat{d}g_i/\hat{d}b > 0$, so almost everywhere continuous differentiability of g_1 in s_i, and, if $s_{-i} = S$, in S, follows from property (c) of m^*, by the implicit function theorem. ■

Proof of Proposition 5. This proof has two steps, following the two parts of the Proposition:

1. The condition $r_{\mathcal{R}} \geq r_{pen}$ is shown to imply $d\Pi_i^{\mathcal{R}}/ds_i$ is strictly decreasing and continuous in s_i and, if $s_{-i} = S$, in S. As in the proof of Proposition 3, this implies $s_{i,\mathcal{R}}^*(S)$ is unique and continuous and weakly decreasing in S, giving a unique, symmetric equilibrium characterised by $s_{i,\mathcal{R}}^*(S_{\mathcal{R}}^*) = S_{\mathcal{R}}^*$. As in 3, for a range of r_s above $\underline{r}_s$, the equilibrium is interior.

2. First it is proved that if $r_{\mathcal{U}} = r_{\mathcal{R}} \geq r_{pen}$ and $r_s \in (\underline{r}_s, \overline{r}_s)$ then $S^*_{\mathcal{R}} < S^*_{\mathcal{U}}$. Since in both policies marginal returns are decreasing in the interest rate, so are the equilibria S^*, and so lowering the unsecured equilibrium to the secured equilibrium would require raising the interest rate.

Step 1.

The liquidity-withdrawal threshold $\bar{b}_i$ is Lipschitz continuous in s_i by Lemma 4, so equality of the two integrands in expression 1.12 at $b = \bar{b}_i$ implies

$$\begin{aligned}\frac{d\Pi_i^{\mathcal{R}}(s_i, s_{-i})}{ds_i} =&(1-\lambda)r_s \\ &+ \lambda\left[\int_0^{\bar{b}(s_i,s_{-i})} \frac{-m^*(b, s_{-i})}{1-m^*(b,s_{-i})} f(b)db + \int_{\bar{b}(s_i,s_{-i})}^{l} -r_{\mathcal{R}} f(b)db\right].\end{aligned} \tag{1.34}$$

By Lemma 4 expression 1.34 is continuous in s_i and, if $s_{-i} = S$, in S. Furthermore,

$$\frac{\hat{d}^2\Pi_i^{\mathcal{R}}(s_i, s_{-i})}{\hat{d}s_i^2} = \lambda \frac{\hat{d}\bar{b}(s_i, s_{-i})}{\hat{d}s_i}\left(r_{\mathcal{R}} - \frac{m^*(\bar{b}_i, s_{-i})}{1-m^*(\bar{b}_i, s_{-i})}\right) f(\bar{b}_i).$$

Lemma 4 shows that $\hat{d}\bar{b}_i/\hat{d}s_i < 0$, so $\hat{d}^2\Pi_i^{\mathcal{R}}/\hat{d}s_i^2 < 0$ by $r^{\mathcal{R}} > r_{pen}$ and positivity of f. Homogeneity of $d\Pi_i^{\mathcal{R}}/ds_i$ across i then implies that any equilibrium must be symmetric.

Given $s_{-i} = S$, Lemma 4 implies

$$\begin{aligned}&\frac{\hat{d}^2\Pi_i^{\mathcal{R}}(s_i, S)}{\hat{d}s_i\hat{d}S} \\ &= \lambda\left[\int_0^{\bar{b}(s_i,S)} \frac{-\frac{\hat{d}m^*(b,S)}{\hat{d}S}}{(1-m^*(b,S))^2} f(b)db + \frac{\hat{d}\bar{b}(s_i,S)}{\hat{d}S}\left(r_{\mathcal{R}} - \frac{m^*(\bar{b}_i,S)}{1-m^*(\bar{b}_i,S)}\right) f(\bar{b}_i)\right].\end{aligned} \tag{1.35}$$

Lemma 4 also shows that $\hat{d}\bar{b}_i/\hat{d}S \leq 0$, and that m^* is weakly decreasing in S, and for m^* greater than but sufficiently close to zero, strictly decreasing in S. Therefore $r^{\mathcal{R}} > r_{pen}$ implies expression 1.35 is negative.

Step 2.

Given b and s, by expressions 1.22 and 1.34 the ex-post marginal return to securities is at least as high in the unsecured lending policy if

$$r_{\mathcal{R}} \geq m^*_{\mathcal{U}}(b, s_{-i})(1 + r_{\mathcal{U}})$$

where $m^*_{\mathcal{U}}$ denotes m^* under the unsecured lending policy. Setting $r_{\mathcal{R}} = r_{\mathcal{U}}$ this rearranges to

$$r_{\mathcal{U}} \geq \frac{m^*_{\mathcal{U}}(b, s_{-i})}{1 - m^*_{\mathcal{U}}(b, s_{-i})}$$

which $r_{\mathcal{U}} > r_{pen}$ implies is true because $M(l+\gamma l) \geq m^*_{\mathcal{U}}(b, s_{-i})$. Since this holds regardless of b, and $m^*_{\mathcal{U}}$ varies with b, it holds with strict inequality in expectation across b. Therefore, if $r_{\mathcal{R}} = r_{\mathcal{U}}$ then $d\Pi_i^{\mathcal{R}}/ds_i < d\Pi_i^{\mathcal{U}}/ds_i$ given s. Since $d\Pi_i^{\mathcal{R}}/ds_i$ is decreasing and continuous in s_i, at any interior optimum $d\Pi_i^{\mathcal{R}}/ds_i = 0$. Accordingly, if $S^*_{\mathcal{U}}$ is interior, which Proposition 3 shows $r_s \in (\underline{r}_s, \overline{r}_s)$ implies, then under the secured lending policy the marginal return to securities at $s_i = S = S^*_{\mathcal{U}}$ is negative, so any fixed point $s^*_{i,\mathcal{R}}(S^*_{\mathcal{R}}) = S^*_{\mathcal{R}}$ must be at lower S. ■

Proof of Proposition 7. This proof shows that if both policies induce the same equilibrium S^*, the secured policy has higher equilibrium Π_i for all i. Therefore, given an optimal unsecured lending policy, a secured lending policy can achieve higher W by inducing the same S^* as the unsecured lending policy. This level of W cannot be lower than that of the optimal secured lending policy.

The proofs of Propositions 3 and 5 show that $d\Pi_i^{\mathcal{U}}/ds_i$ and $d\Pi_i^{\mathcal{R}}/ds_i$ are continuously decreasing in s_i so interior equilibria must satisfy $d\Pi_i^{\mathcal{U}}/ds_i = d\Pi_i^{\mathcal{R}}/ds_i = 0$. Say this occurs at symmetric $S^*_{\mathcal{U}} = S^*_{\mathcal{R}} = S_1$. Define $m^*_{\mathcal{U}}(b)$ and $m^*_{\mathcal{G}}(b)$ as the functional forms in expression 1.4 when $S = S_1$, define $\bar{b}_1$ as $\bar{b}(S_1, S_1)$, and define $m^*_{\mathcal{R}}(b)$ as the market price in the secured lending policy whenever $b > \bar{b}_1$ and $s = S_1$. Equating the marginal returns in expressions 1.22 and 1.34 gives

$$\int_{\bar{b}_1}^{l} -m^*_{\mathcal{U}}(b)(1 + r_{\mathcal{U}})f(b)db = \int_{\bar{b}_1}^{l} -r_{\mathcal{R}}f(b)db. \tag{1.36}$$

From the payoff functions in expressions 1.9 and 1.12, the inequality $\Pi_i^{\mathcal{R}}(S_1, S_1) > \Pi_i^{\mathcal{U}}(S_1, S_1)$ holds if and only if

$$\int_{\bar{b}_1}^{l} \left[(b + S_1 m^*_{\mathcal{U}}(b) - l)(1 + r_{\mathcal{U}}) - (b + S_1 m^*_{\mathcal{R}}(b) - l)\frac{r_{\mathcal{R}}}{m^*_{\mathcal{R}}(b)}\right] f(b)db > 0. \tag{1.37}$$

After this paragraph a series of relations are presented; their corresponding explanations are as follows: the first (equality) is a rearrangement of terms; the second (inequality) holds because $m^*_{\mathcal{U}}(b) > m^*_{\mathcal{R}}(b)$ for all $b > \bar{b}_1$; the third (equality) applies expression 1.36 to remove the $S_1 m^*_{\mathcal{U}}(b)$ term; and the fourth (equality) applies expression 1.36 to substitute out $1 + r_{\mathcal{U}}$ and then rearranges terms.

$$\int_{\bar{b}_1}^{l} \left[(b + S_1 m^*_{\mathcal{U}}(b) - l)(1 + r_{\mathcal{U}}) - (b + S_1 m^*_{\mathcal{R}}(b) - l)\frac{r_{\mathcal{R}}}{m^*_{\mathcal{R}}(b)} \right] f(b)db$$

$$= \int_{\bar{b}_1}^{l} \left[(b + S_1 m^*_{\mathcal{U}}(b) - l)\left((1 + r_{\mathcal{U}}) - \frac{r_{\mathcal{R}}}{m^*_{\mathcal{U}}(b)} \right) + (l - b)\left(\frac{r_{\mathcal{R}}}{m^*_{\mathcal{R}}(b)} - \frac{r_{\mathcal{R}}}{m^*_{\mathcal{U}}(b)} \right) \right] f(b)db$$

$$> \int_{\bar{b}_1}^{l} (b + S_1 m^*_{\mathcal{U}}(b) - l)\left((1 + r_{\mathcal{U}}) - \frac{r_{\mathcal{R}}}{m^*_{\mathcal{U}}(b)} \right) f(b)db$$

$$= \int_{\bar{b}(S_1,S_1)}^{l} (l - b)\left(\frac{r_{\mathcal{R}}}{m^*_{\mathcal{U}}(b, S_1)} - (1 + r_{\mathcal{U}}) \right) f(b)db$$

$$= r_{\mathcal{R}} \left[\int_{\bar{b}_1}^{l} (l - b)\frac{1}{m^*_{\mathcal{U}}(b)} f(b)db - \frac{\int_{\bar{b}_1}^{l} f(b)db}{\int_{\bar{b}_1}^{l} m^*_{\mathcal{U}}(b) f(b)db} \cdot \int_{\bar{b}_1}^{l} (l - b) f(b)db \right].$$

Because $b \geq \bar{b}_1$ implies $m^*_{\mathcal{U}}(b) > 0$, the following inequality follows from Jensens' inequality

$$\frac{\int_{\bar{b}_1}^{l} f(b)db}{\int_{\bar{b}_1}^{l} m^*_{\mathcal{U}}(b) f(b)db} = \frac{1}{E[m^*_{\mathcal{U}}(b) | b \geq \bar{b}_1]} < E\left[\frac{1}{m^*_{\mathcal{U}}(b)} \middle| b \geq \bar{b}_1 \right] = \frac{\int_{\bar{b}_1}^{l} \frac{1}{m^*_{\mathcal{U}}(b)} f(b)db}{\int_{\bar{b}_1}^{l} f(b)db}.$$

So, given that an interior equilibrium requires $r_{\mathcal{R}} > 0$, a sufficient condition for expression 1.37 is

$$\int_{\bar{b}_1}^{l} (l - b)\frac{1}{m^*_{\mathcal{U}}(b)} f(b)db \cdot \int_{\bar{b}_1}^{l} f(b)db > \int_{\bar{b}_1}^{l} (l - b) f(b)db \cdot \int_{\bar{b}_1}^{l} \frac{1}{m^*_{\mathcal{U}}(b)} f(b)db.$$

This holds by Chebyshev's inequality because $l - b$ and $1/m^*_{\mathcal{U}}(b)$ are both decreasing in b, the latter from Lemma 1. ■

Proof of Proposition 8. Take an optimal unsecured policy equilibrium $S^*_{\mathcal{U}}$ and set $\bar{s} = S^*_{\mathcal{U}}$. Assuming no banks fail under this policy, the marginal return to securities for bank i is

$$\frac{d\Pi_i^S(s_i, s_{-i})}{ds} = (1-\lambda) r_s + \lambda \left[\int_0^{\underline{b}} \frac{-m^*(b, s_{-i})}{1 - m^*(b, s_{-i})} f(b)db + \int_{\underline{b}}^{l} \frac{-(l - b)}{\bar{s} + b - l} f(b)db \right]. \tag{1.38}$$

Given s, equation 1.38 is greater than that of the unsecured lending policy (equation 1.22). For instance, for $b < \underline{b}$ market illiquidity equals $M(b(1 + \gamma) + S - l)$

under both policies, and for $b \geq \underline{b}$, the term $-(l-b)/(\overline{s}+b-l)$ is increasing in b whereas $-m^*_{\mathcal{U}}(b, s_{-i})(1+r_{\mathcal{U}})$ is decreasing in b. Therefore the absence of unsecured-lending equilibria at $S < S^*_{\mathcal{U}}$ implies the absence of securities-purchase equilibria at $S < S^*_{\mathcal{U}}$.

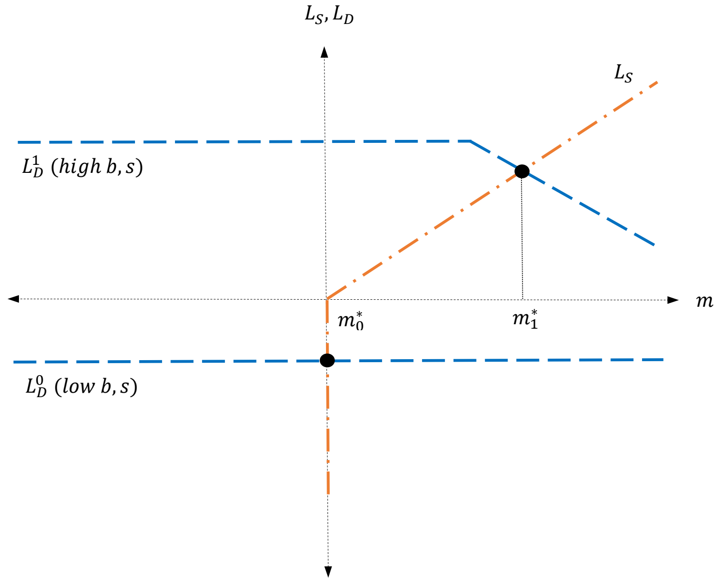
If banks choose higher s, the authority must raise $\overline{s}$ to meet its objective of preventing bank failures. Given this, there exists an equilibrium at $s = \overline{s} > S^*_{\mathcal{U}}$. Observe that if $\overline{s}$ in equations 1.14 and 1.38 is replaced with S, such that $\overline{b} = \overline{b}(S)$, expression 1.38 is continuous in S. Therefore, either at some $S > S^*_{\mathcal{U}}$ equation 1.38 equals zero, which is an equilibrium, or equation 1.38 is positive at $S = l$, which is an equilibrium. ■

Proof of Proposition 12. At date 0, securities necessarily pay negative expected returns for 'highly liquid' banks so these banks hold $s_i = 0$. With the following changes, all previous proofs maintain validity for the other banks:

- Payoff functions and their derivatives apply only to banks that are not highly liquid.
- s and s_{-i} are redefined to exclude highly liquid banks.
- S, including with any superscript/subscript/accent/combination of these, is replaced with $S_{ilqd} = \int_0^1 s_i di/(1-\delta)$, except in the following instances:
  - In the proof of Lemma 1, the equations $L_D = b(1+\gamma) + S - l$, $\hat{b}(s) = (l-S)/(1+\gamma)$, $S \leq \hat{b}^{-1}(b)$ and $S = \hat{b}^{-1}(b)$.
  - In the proof of Lemma 4, the statements $S \leq \hat{b}^{-1}(b)$ and $S > \hat{b}^{-1}(b)$.
  - In expression 1.28, in the body of the function but not in the conditions.
  - In the proof of Proposition 7, the reference to expression 1.4.
  - In the proof of Proposition 8, where S appears in the M function.

■

Figure 1.1: Date 1 securities market clearing



Notes: L_S is consistent with expression 1.1 and L_D is from expression 1.4. The axis lines are at zero.

Figure 1.2: Model timeline

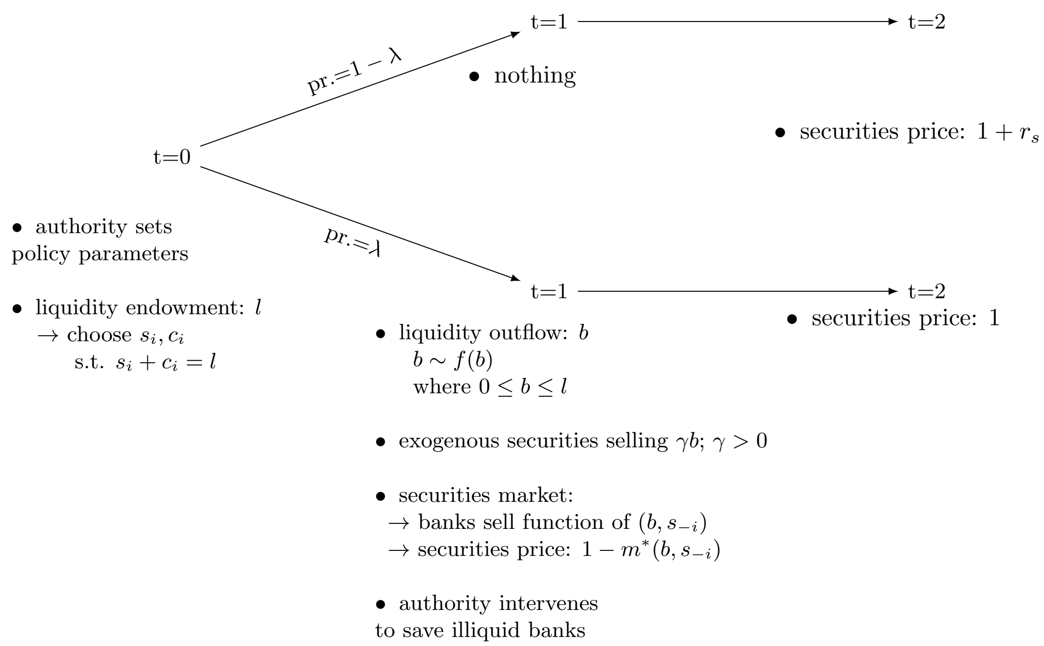
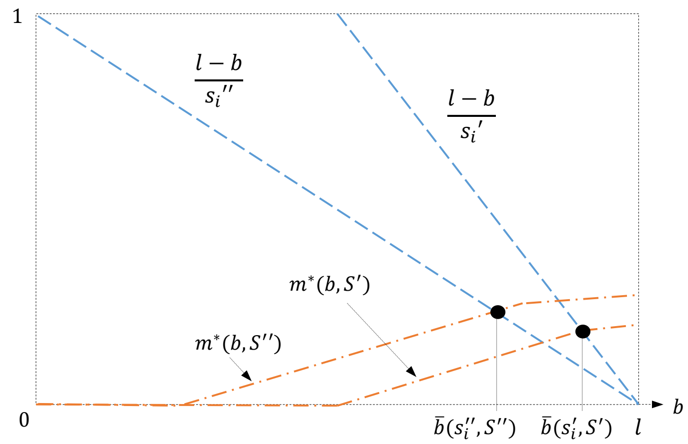


Figure 1.3: Market illiquidity, a bank's capacity to handle it, and $\bar{b}_i$



Notes: m^* is as characterised in expression 1.4 with $M(L_D) = \max\{\alpha L_D, 0\}$ and $0 < \alpha < 1/(l + \gamma l)$. The securities values satisfy $s_i' = S' < S'' < s_i'' = l$.

Chapter 2

REPO AND UNSECURED INTERBANK MARKETS UNDER STRESS: SUPERVISORY TRANSACTION-LEVEL EVIDENCE

2.1 Introduction

In mid September 2008 the failure of Lehman Brothers triggered a global financial crisis characterised by disruptions to wholesale funding liquidity around the world. In bank-dominated economies, interbank markets took centre stage as banks' perceptions of counterparty risk intensified and benchmark unsecured interbank interest rates reached historical peaks (the Ted spread exceeding three percentage points). Safe (high quality debt) assets became the most reliable means for maintaining liquidity, and a flight to safety ensued (e.g. Kacperczyk and Schnabl 2010).

Despite the fact that, during the 2008 global financial crisis, the repo (secured) interbank market became more important than the unsecured market (European Central Bank 2010), interbank repo transactions have not been analysed at the same level of granularity as unsecured markets, due to a lack of comprehensive transaction-level repo data.[1] Our main contribution to the literature is to fill this void and, moreover, to analyse how the two sides of interbank funding liquidity markets – unsecured and secured (i.e. repo) – react and interact in response to

[1] See Afonso et al. (2011) for granular interbank unsecured data.

strong financial shocks.

Australia provides an excellent platform for identification, as it has supervisory, proprietary loan-level data for both the repo and unsecured interbank markets (which both use the same form of infrastructure); and the global financial crisis was exogenous to the Australian economy and its interbank market (the real-estate market did not crash and there was no economic recession). As we will argue in detail, loan-level data is necessary to disentangle borrower (counterparty) risk from lender (e.g. liquidity hoarding) motives, as interbank markets are characterised by endogenous matching. Furthermore, it is necessary to simultaneously analyse the repo and unsecured interbank markets because banks may be substitute between them.

We find that overall financial stress (proxied by the US TED spread) leads to an expansion of the repo market, and banks' relative activity in the unsecured and repo markets depends on borrower (more than lender) balance-sheet strength and high-quality collateral holdings. While the repo-market expansion is almost entirely driven by the second-best (but still high-quality) collateral – consistent with a demand-driven scarcity of the first-best collateral, indicated by its repo rates falling around 100 basis points relative to second-best collateral – there is relative market segmentation depending on banks' ex-ante type of collateral holdings. Indeed, the strongest substitution from unsecured to secured markets is by risky (borrower) banks with plentiful first-best collateral. We contribute to the academic literature by revealing that interactions between the two markets occur and are heterogeneous across banks and collateral types. This helps to provide a holistic understanding of interbank markets and to discriminate among different theories about their functioning. For example, we show that only analysing the unsecured market can lead to misleading conclusions, as repo markets can absorb liquidity demand unmet in the unsecured market, and, provided banks have sufficient collateral, risky borrowers offset a reduction of unsecured borrowing with an increase in repo borrowing. Importantly, these dynamics can be affected by relative availability of different forms of high-quality collateral. Our paper also isolates the effect of collateral from that of infrastructure by directly comparing repo and unsecured markets that operate through the same market structure. We show that the two markets behaved differently in aggregate and in composition, demonstrating that the collateralization itself is a key determinant of market functioning.

We have interbank market data at the transaction – i.e. *borrower-lender-day-market-collateral* – level. That is, we have transaction data for each interbank market, repo and unsecured, including information on the collateral provided, which we combine with bank balance-sheet data.[2] Both the unsecured and secured interbank markets in Australia are over the counter (OTC) and bilaterally cleared, so differences in market behaviour cannot be attributed to differences in market infrastructure. The interbank repo market is mostly collateralized by Australian Government securities (AGS), issued by the federal government, and by securities issued by the Australian state governments (SGS). AGS are the safest and most liquid – the Australian Government has relatively low debt – but SGS are also considered very safe, and are included in the regulatory definition of 'high quality liquid assets'.[3]

In Australia the financial stress was exogenously transmitted from other parts of the world, unlike countries with financial stress endogenously generated within the financial system. Australia did not experience a real estate credit boom prior to the crisis (different from e.g. the US, the UK, Ireland and Spain) and Australian banks did not hold significant US subprime securities (different from e.g. German and other European banks). The major domestic banks in Australia remained profitable throughout the 2008 crisis, none of the interbank market participants failed, and Australia did not experience an economic recession. Nevertheless, the financial crisis was heavily felt. When the TED spread rapidly tripled in mid-September so did the equivalent interbank rate in Australia. Bank bond issuance stalled, and these conditions ultimately led to a strong government and central-bank intervention starting in the second week of October (with guarantees over the wholesale market and the largest monetary policy rate reduction in 15 years).

To identify interactions between the repo and unsecured wholesale markets for funding liquidity, we analyse data at the transaction level and exploit the US TED spread to obtain exogenous time-varying shocks to financial market-wide stress. Transaction-level data are important as there may be endogenous matching between borrowers and lenders in the interbank market. For example, the theoretical literature argues that monitoring incentives and diversification motives are important for interbank transactions (Rochet and Tirole 1996; Freixas and Rochet 2008; Allen and Gale 2009), which implies that lenders choose their borrowers in similar (for monitoring) or in different (for risk diversification) businesses and geographical areas. In consequence, data that identify both borrowers and lenders, such as loan- or transaction-level data, are necessary to disentangle borrower (counterparty) risk from lender (e.g. liquidity hoarding) motives.

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[2]The transaction data come from the Australian central debt-securities depository, Austraclear, and from the Reserve Bank of Australia's (RBA) interbank payments system, the Reserve Bank Information and Transfer System (RITS).

[3]Lancaster and Dowling (2011) describe the SGS market in detail.

Using these transaction-level data we analyse lending over each day in each market, and the difference between markets, regressing them on an interaction between the TED spread and counterparties' ex-ante risk and collateral characteristics. Following the credit channel literature (e.g. Khwaja and Mian 2008; Jiménez et al. 2017), we saturate the regressions with fixed effects to control for unobserved variation. For example, when analysing unsecured and secured markets individually, we use borrower*lender fixed effects to ensure that differences in behaviour across borrowers are not driven by the lenders they engage with; when analysing substitution between the secured and unsecured markets, we use borrower*lender*day fixed effects to wash out all influences that are common to both markets, such as time-varying relationships. For robustness, we run placebo regressions using September 2006 data (a year without any financial crisis).

In the weeks before and after the Lehman Brothers default in mid September 2008, the size of the repo market (as compared to the unsecured market) considerably picks up alongside the rise in the TED spread (see Figure 2.8). In early September the repo market is around a third the size of the unsecured market, whereas by early October it outsizes the unsecured market. Before the TED significantly increases, when a borrower bank needs more liquidity its volume is positively correlated between the repo and unsecured market, satisfying demand using both markets. However, when the TED is high after the Lehman Brothers failure, this correlation becomes negative, suggesting that banks face frictions in accessing both markets. Moreover, the negative relationship is more pronounced for riskier borrowers with large holdings of high quality collateral.[4]

Our results, based on highly granular data, show that when the US TED spread rises, unsecured interbank borrowing becomes negatively related to borrower banks' balance-sheet health (measured by non-performing loans (NPL)).[5] In the secured interbank market, however, borrowing becomes positively related to borrower banks' collateral holdings. Moreover, in the repo market the pickup in borrowing is stronger for banks with large (high-quality) collateral holdings *and* high NPL. In our main specification, explicitly analysing the difference across secured and repo markets, we find a significant substitution from the unsecured to the repo market by these high NPL and high collateral borrowers. This occurs both in market participation (i.e. the extensive margin), and in the volume of loans outstanding. Lender behaviour is not consistent with liquidity hoarding (e.g. Acharya and Skeie 2011; Gale and Yorulmazer 2013), in line with previous findings for un-

[4]Mancini et al. (2015) also find a negative relationship between repo and unsecured market volumes in Europe using aggregated data.

[5]A similar pattern occurs in the US unsecured interbank market (see Afonso et al. 2011).

secured market (e.g. Afonso et al. 2011). That is, lenders' risk does not negatively affect lending behaviour, and riskier lenders with good collateral actually increase lending in the unsecured market relative to others. In contrast, riskier borrowers without collateral reduce borrowing in both markets. Our results are not driven by size or foreign versus domestic ownership, and do not show up in placebo tests run on data before the crisis.

While the repo-market expansion is almost entirely driven by the second-best collateral (SGS), the strongest substitution from unsecured to secured markets is by risky borrowers with plentiful first-best (AGS) collateral. In particular, our results suggest that the demand for and scarcity of AGS collateral pushes the repo market into SGS repos. When the TED spread rises and the SGS repo market expands, the size of the AGS repo market remains constant. At the same time, interest rates on AGS repos fall around 100 basis points below rates on SGS repos.[6] Moreover, borrowers move into the market of the collateral they already held (relative market segmentation),[7] although the interaction between borrower risk and borrower collateral holdings is stronger for the AGS market, consistent with these securities providing lenders more reliable protection against the riskier borrowers. Indeed, borrowers with high risk and large AGS holdings shift from the SGS (second best) to the AGS (the best) collateral in the repo market, but no opposite substitution occurs for risky borrowers with large SGS holdings.

Contribution to the literature. The main contributions of our paper are to provide a transaction-level analysis of the repo market, and a detailed side-by-side analysis of the repo and unsecured markets, under stress. This permits identification of how counterparty characteristics affect market functioning that has not previously been possible. To date the most comprehensive analyses of repo markets during the crisis use data that are ether not at a daily (or higher) frequency, or that do not identify both counterparties to each repo position. Moreover, these studies each focus on particular repo market segments that are served by different infrastructure, which makes it difficult to disentangle the effects of infrastructure, collateral and counterparty characteristics. Adrian et al. (2014) write about the need for more comprehensive loan-level repo data. We exploit comprehensive transaction-level data in repo (and unsecured) interbank markets to understand how these markets behave under stress.

Gorton and Metrick (2012b,a) analyse market-level data on repo rates and haircuts

[6] This is consistent with a clear ranking of liquidity value, as found by Bartolini et al. (2010) for government and agency securities in the US market.

[7] Banks with higher ex-ante SGS holdings borrow more against SGS, whereas banks with higher ex-ante holdings of AGS borrow more against AGS.

in the bilateral segment of the US repo market, in which dealers trade with other dealers and entities such as hedge funds and foreign institutions. They find a substantial tightening, particularly for lower quality collateral related to asset backed securities (ABS). Copeland et al. (2014) and Krishnamurthy et al. (2014) analyse daily borrower-level data and quarterly loan-level data (respectively) on the triparty repo segment, in which dealers mostly borrow from money market funds and other nonbank institutions, finding conditions to be more stable than in the bilateral segment, particularly for repos against government-backed collateral.[8] Mancini et al. (2015) analyse market-level data (separated by collateral type) on the centrally cleared segment of the European repo market, finding that activity against good quality collateral expanded while markets against lower quality collateral shrunk, and that aggregate volumes in the bilateral market segment also declined. They conclude that the market infrastructure was more important than the collateral in ensuring repo market stability. Martin et al. (2014b) also demonstrate in a theoretical model that repo market infrastructure can be important for avoiding repo runs that are comparable to traditional bank runs (e.g. Diamond and Dybvig 1983; Goldstein and Pauzner 2005). Our paper isolates the effect of collateral from that of infrastructure by directly comparing repo and unsecured markets that operate through the same market structure (i.e. both are OTC). We show that the markets behave differently in aggregate and in composition, demonstrating that the collateralization itself is a key determinant of market functioning.

Studies of unsecured interbank markets during the crisis have used more granular data than studies of repo markets. Afonso et al. (2011) find that in the US, during the peak stress around the Lehman Brothers failure, large and risky unsecured debtors borrowed less, from a smaller number of counterparties, and experienced higher volatility in interest rates. Angelini et al. (2011) analyse the segment of the European unsecured market traded through the e-MID platform, finding that larger banks and safer banks were charged lower rates on their borrowing relative to aggregated market-wide repo rates, in contrast to pre-crisis times. However, we show that only studying the unsecured market can be misleading. Repo markets can absorb liquidity demand unmet in the unsecured market, and, provided they have sufficient collateral, risky borrowers offset a reduction of unsecured borrowing with an increase in repo borrowing.

Much of the repo-market theory focuses on potentially destabilizing effects of a change in collateral value, as observed, for example, during the crisis in parts of the US repo market. Gorton and Ordoñez (2014) and Dang et al. (2015) provide

[8]Triparty repos are conducted through centralized settlement and custodial services offered by two large clearing banks (Copeland et al. 2012).

a compelling description of how repo markets against lower-quality collateral can rapidly dry up as securities switch from information insensitive to information sensitive. If the uncertainty around a security's underlying value reaches a critical threshold, investing in costly information acquisition becomes preferable before receiving the security, which introduces trading frictions and asymmetric information into the market. Other papers demonstrate how an increase in haircuts can introduce destabilizing feedback loops by forcing a withdrawal of liquidity from interbank funding markets (Gai et al. 2011; Martin et al. 2014a) and from underlying secondary markets for the collateral (Brunnermeier and Pedersen 2009). There is also a substantial macro literature on the potentially nonlinear effects of a change in collateral value (e.g. Kiyotaki and Moore 1997; Brunnermeier et al. 2012).

However, information-sensitive collateral was more prevalent in the US repo market than, for example, in Europe or Australia. Martin et al. (2014b) argue that repo markets are run proof if the collateral is high enough quality, consistent with the studies that show robust functioning of some repo markets during the crisis (Copeland et al. 2014; Krishnamurthy et al. 2014; Mancini et al. 2015). Regulators have acknowledged this with heavy emphasis on holdings of 'high quality liquid assets' in the post-crisis Basel reforms. Indeed, performance of repo markets with high quality collateral may be more relevant for understanding how markets may function in the future. We show that different types of collateral within the high-quality category behaved differently – the large expansion of the repo market after the Lehman Brothers default was driven by the second-best collateral, while rates on repos against first-best collateral substantially dropped, consistent with a demand-driven scarcity. However, we also find evidence that riskier borrower banks needed the very best collateral to neutralize the reduction in borrowing in the unsecured market.

The theoretical literature most closely corresponding to our work relates to participation in interbank markets with counterparty risk. Freixas and Holthausen (2004) and Heider et al. (2015) demonstrate that riskier banks will suffer worse terms in unsecured interbank markets, and asymmetric information about counterparty risk can lead to market dry-ups when lower quality banks are more likely to seek borrowing than high-quality banks. Heider and Hoerova (2009) explicitly analyse the role of repo markets in mitigating counterparty risk relative to unsecured markets, and make several empirical predictions that align with our results. First, demand for repo borrowing will be stronger for banks with higher credit risk. Our evidence suggests this is true only to the extent that these banks have collateral available – the strongest substitution from unsecured to repo markets is by risky borrowers with plentiful collateral. In their model borrowers have homogeneous ex-ante collateral holdings which then determine the level of aggregate repo activity. We show that a similar pattern occurs in the cross section – banks with more collateral than others increase their repo borrowing more than others. Second, they argue that in episodes of heightened credit risk the repo rate will fall further below the unsecured rate, as tightened conditions in the unsecured market increase the desire to hold bonds that can be used as collateral. We find that rates on first-best (AGS) repos fall well below the unsecured rate just after the Lehman Brothers default. Third, their model shows that the more scarce is collateral, the lower its repo rate, because it will be more sensitive to changes in demand for its use as collateral. We find that of the two prevalent collateral types – AGS and SGS – rates on repos against the more scarce AGS fall well below rates on repos against the less scarce SGS.

2.2 Institutional setup, data and empirical strategy

2.2.1 Institutional background

During our sample the Australian repo and unsecured interbank markets were completely over-the-counter markets, with loans negotiated directly between counterparties and settled bilaterally through the Australian payments and securities settlements infrastructure. Unsecured lending takes place via payments between banks' exchange settlement accounts (ESAs) held at the Reserve Bank Information and Transfer System (RITS), the Reserve Bank of Australia's (RBA) real-time gross settlement system. All banks licensed to operate in Australia, including Australian banks and subsidiaries and branches of foreign banks, must have an ESA, permitting them to directly transfer central bank money (i.e. 'cash') to each other in real time. During 2008 there were around 50 banks with RITS ESAs.

Whereas an unsecured loan takes place through a series of cash payments in RITS, a repo loan resembles a series of securities transactions, with a cash loan and collateral provision occurring in an initial transaction, and a later loan repayment and collateral return. In Australia these transactions take place through Austraclear, Australia's settlement system and central securities depository (CSD) for debt securities, which is a subsidiary of the publicly listed company ASX. Austraclear has capability to feed payments instructions into RITS, permitting account holders to instruct Austraclear to simultaneously transfer, in opposite directions, debt securities across Austraclear accounts and cash across RITS accounts. The regulatory term for this simultaneous transfer, which is a key protection against settlement risk, is delivery-versus-payment (DvP) settlement. Entities that hold an Austraclear account but not an ESA execute DvP securities settlements by having another bank with an ESA hold and transfer cash in RITS on their behalf. In September 2008 there were roughly 360 active Austraclear accounts belonging to around 180 separate entities.

The RBA plays a prominent role in both interbank markets. Its target policy rate is the average rate on overnight unsecured loans, and the target is achieved by controlling the aggregate supply of ESA balances via repo auctions each morning. Due to a combination of strong commitment by the RBA and relatively low counterparty risk, the target is achieved with very high precision – there is virtually no cross-sectional variance around the target rate. The total value of RBA repos is large relative to the size of Australian interbank markets, typically representing more than half of the total repo value outstanding, although RBA repos tend to have maturities ranging between one and several weeks, whereas the interbank repo market is focused on maturities of less than one week. A substantial proportion of RBA repos are against private securities, whereas the interbank repo market is heavily concentrated in Australian Government securities (AGS) and securities issued by the Australian state governments (SGS). AGS play a similar role in Australia to Treasuries in the US, as the safest and most liquid assets, all rated AAA (or equivalent), while SGS are still considered very high quality, all with ratings of AAA or AA+ (or equivalent).

Banks use both markets to manage short-term liquidity needs arising from other business activities, and the repo market also acts as a source of funding for securities holdings (Becker et al. 2016; Hing et al. 2016). In our sample there is heavy overlap in participation – all of the 17 banks active in the repo market are also active in the unsecured market, and there are another 14 banks active only in the unsecured market. Roughly three quarters of the banks in the unsecured market and half of the banks in the repo market have foreign parents (Table 2.2), which are mostly very large international banks from the US, the UK, Europe and Asia. The sample of Australian banks includes all of the major Australian banks and some smaller Australian financial institutions. Data from the Australian prudential regulator indicate another market segment of repos against Australian securities, being carried out through securities settlement systems located in Europe, and therefore not appearing in our data. Since the unsecured market takes place through Australian infrastructure that is connected to Austraclear, these repo counterparties' choice to use foreign infrastructure makes these repos less likely to be between pairs that also participate in the Australian unsecured interbank market. We therefore exclude them from our definition of the Australian interbank market.[9]

[9] This is discussed further in Section 2.2.3.

Several of these institutional features make Australia an ideal setting for comparing repo and unsecured interbank funding markets during the crisis. First, both markets were completely bilateral, so differences in behaviour are not attributable to infrastructure. In Europe, unsecured interbank lending was predominantly bilateral whereas during the crisis, potentially close to half of the repo market was triparty or centrally cleared.[10] Since market infrastructure such as central counterparties fundamentally alter the role of counterparty risk in that market, it is difficult to determine whether a difference in behaviour between the repo and unsecured markets is attributable to repos being secured by collateral or repos utilizing different infrastructure. Using European data, Mancini et al. (2015) provide results consistent with a stress-driven substitution from unsecured lending to centrally cleared repo lending, but attribute this reaction more to the infrastructure rather than the role of collateral in a repo.

Second, all banks active in the repo market were also active in the unsecured market, and the high degree of overlap in participation permits a direct comparison by analysing substitution between markets. In contrast, the US unsecured market primarily comprises depository institutions, while the repo market is more heavily concentrated in lending between dealers, money market funds, securities lenders, hedge funds and non-US institutions (Afonso et al. 2011; Krishnamurthy et al. 2014; Gorton and Metrick 2012b).

Third, the strong presence of foreign-owned banks in the Australian financial system contributes two valuable features to the analysis. Figure 3.1 shows that the key measure of risk in the Australian interbank market shot up at the same time as the key measure for the US, just after Lehman Brothers defaulted on 15 September.[11] Given the central role of the US financial system in the global economy, compared to Australia's relatively small financial system, it is infeasible that Australian conditions could have driven the unprecedented volatility in US interbank market conditions. Neither Lehman Brothers nor AIG, the two entities that caused much of the stress in this period, were direct participants in the Australian interbank markets. Rather, the strong comovement is likely driven by international linkages of the Australian financial system, including the prominence of foreign banks in the interbank market. Therefore we can use a measure of foreign stress, such as the TED spread as an exogenous and material driver of market stress in Australia. Moreover, the strong presence of major international banks in our sample presents a commonality between Australian and other regions' interbank

[10]European Central Bank (2009) states that when banks began reporting their repo clearing arrangements in 2009, just under 50 per cent of repos were reported as triparty or centrally cleared.

[11]The TED spread is lagged one day to align the measures across time zones.

markets that suggests our results are somewhat representative for other countries.

2.2.2 The financial system leading into the crisis

The Australian financial system resembles those of other developed countries. In 2007, Australia's bank assets were 114 per cent of GDP, relative to an average of 131 per cent across high-income OECD countries (Davis 2011). Australian banks are relatively concentrated in residential real-estate loans, which in 2009 comprised 59 per cent of all loans, compared to, for example, 15 and 38 per cent for the United Kingdom and the United States respectively. Nonetheless, all the major Australian banks remained profitable throughout the crisis, in part attributable to low investment in subprime mortgages relative to banks in other countries. This helped Australia to weather the period without a recession, experiencing a single quarter of negative GDP growth at end 2008.

The liability composition of banks in Australia was reasonably stable throughout 2008 (Figure 2.2). Short-term funding remained around a third of total funding, but slightly declined in 2008 with deposits picking up as the global instability led banks to shift towards the most stable funding sources. Notwithstanding, funding conditions tightened substantially. The spread on Australian banks' short-term paper reached historical highs (Figure 3.1), and September saw banks' total bond issuance fall to under a third of typical monthly issuance (Figure 2.3). On 28 November the Australian Government implemented a guarantee on banks' large deposits and wholesale debt (following similar guarantees in other countries), and the subsequent surge in bond issuance is further indicative of funding tightness prior to the guarantee.

The funding tightness can also be seen in the rapid rise of ESA balances to historical highs around when Lehman Brothers defaulted on 15 September (Figure 2.4). The expansion of ESA balances was driven by RBA repos against lower quality securities, as banks preferred to hold onto their safest securities for other purposes (Ewerhart and Tapking (2008) provide theory describing this phenomenon). On 8 October, immediately after our sample end, the RBA expanded its acceptable repo collateral to include a wider range of residential mortgage-backed securities and asset-backed commercial paper, and offered repos of extended maturities, to further facilitate banks' heightened demand for liquidity. On the same day, the RBA lowered its policy rate by one per cent, the only change greater than half a per cent in magnitude since 1992. This rapid easing occurred a day before the unscheduled decisions by the Bank of England, the European Central Bank and the Federal Reserve to each cut policy rates by half a per cent.

2.2.3 Data sources

To our knowledge, we are the first study to analyse loan-level data covering repo and unsecured markets. The loan-level repo data, and our data on participants' collateral holdings, come from two proprietary datasets that contain all overnight holdings and intraday changes in holdings (i.e. transactions) of non-discount debt securities through Austraclear. Discount securities issued by non-government entities, i.e. private securities without coupon payments, are the only debt securities excluded from the datasets; prudential data indicate these could comprise up to a quarter of the repo market. Aside from these discount securities, the transactions data contain every change in ownership of AUD-denominated debt securities except for those that take place within a single Austraclear account (and therefore require no movement of securities).

Transactions can occur within the same Austraclear account if neither entity owns and uses its own account and both entities employ the settlement services of the same Austraclear account holder. As mentioned in Section 2.2.1, the most common example of this would probably be transactions involving securities stored in Austraclear, but initiated via international CSDs (ICSDs). ICSDs permit their members to settle Australian securities without becoming members in the Australian settlement infrastructure. Essentially, the ICSD uses a single Austraclear account, and keeps its own records of its members' transactions with each other, while the securities do not move from inside its account. Prudential data indicate there could be substantial activity in these repos. However, they cannot occur with DvP settlement of AUD central-bank money because the ICSDs have no direct connection to RITS. Instead, the cash side of the repo is settled across the books of a private bank employed by the ICSD. We choose to define the Australian market as excluding these repos, since entities with Austraclear accounts are more likely to prefer settlement in central bank money. A more detailed discussion is in Garvin (2018).

Our securities transaction data include information on the date and time of the transaction, the face value and international securities identification number (ISIN) of transferred securities,[12] the quantity of cash transferred in the opposite direction (sometimes zero), and the Austraclear accounts sending and receiving the securities. To identify the securities transactions that comprise repos, we use the algorithm in Garvin (2018), which detects pairs or groups of transactions that involve the same counterparties, the same type and face value of securities, and money quantities consistent with a feasible repo rate. We calibrate the algorithm to detect

[12]The ISIN is the standard identifier for securities. Two securities with the same ISIN are equivalent for trading purposes.

repos open for eight days or less with implied interest rates between 3 and 7.25 per cent, which the data indicate are realistic bounds.[13] The detailed analysis in Garvin (2018) indicates that the algorithm detects repos transacted through Austraclear with high accuracy.

The unsecured lending data come from a proprietary transaction-level dataset that contains all payments through RITS. We use the algorithm in Brassil et al. (2016) to identify which payments are interbank loans. Brassil et al. (2016) enhance the Furfine (1999) algorithm, which detects pairs of transactions that comprise interbank loans, to detect loans that involve more than two transactions, and provide evidence that this considerably reduces the quantity of loans missed by the algorithm. Both our repo and unsecured datasets therefore capture loans whose principal is increased or decreased (or both) before it is fully repaid. However, due to the transaction-level nature of the data, we cannot explicitly distinguish between overnight loans that are subsequently extended (i.e. rolled over) without transacting, and loans that upon initiation are agreed to be for multiple days (i.e. term loans). Our analysis groups these loan types together and puts little emphasis on maturities, instead focussing on total quantity of loans outstanding at any point in time.

Table 2.1 provides summary statistics at the loan level. There are 793 unsecured loans and 797 repo loans. Unsecured loans are larger than repo loans (medians of $100 million and $23 million respectively) but open for fewer days (medians of 1 and 4 days respectively). Loan sizes in both markets are heavily positively skewed. AGS collateralised loans are more frequent, smaller, and open for fewer days than SGS collateralised loans. The median interest rate on AGS repos is 20 basis points below the cash rate (i.e. the policy target rate) and the median SGS repo rate is equal to the cash rate.

Data relating to entities' balance sheets are from SNL Financial or, if unavailable or obviously erroneous, from public financial reports.[14] The TED spread data are from the Federal Reserve Bank of St. Louis website.

[13]Specifically, this is the widest interest-rate range at which repos are detected with the following characteristics: the implied interest rate is the same when rounded to four and five decimal places; there are at least two other detected repos at the same rate (rounded to four decimal places); and the repo is not between two 'client' designated accounts.

[14]We find an outlier in the SNL data that is inconsistent with its public financial statements.

2.2.4 Sample and variables

Our analysis is based on loans open during a four week period from Monday 8 September to Friday 3 October 2008. The securities transactions and payments data we use to form our sample (discussed in Section 2.2.3) extend from 1 September to 10 October; we use a shorter sample of loans outstanding to avoid attenuation at the sample ends resulting from a several-day loan not being detectable if one of its transactions occurs outside the transactions sample. Our sample ends on Friday 3 October just prior to major RBA interventions specifically targeting interbank markets. As described in Section 2.2.1, early the following week the RBA loosened its collateral requirements and extended the maturities of RBA repos, with the explicit purpose of easing liquidity conditions for banks. The effect of this policy change on individual banks was likely related to the bank characteristics we use as explanatory variables, changing the nature of the relationships we wish to analyse. For placebo regressions we also analyse a four week sample of corresponding data covering 8 September 2006 to 5 October 2006.

Banks are grouped at the parent company level, in some instances requiring aggregation across multiple Austraclear accounts. The Austraclear account names indicate whether the owner uses the account for proprietary or client purposes, and accounts indicated as for client purposes are treated as a separate entity to the parent company.[15] We remove one non-major Australian bank owing to in-sample corporate activity relating to its takeover by another Australian bank. The majority of non-client entities (i.e. banks) are foreign, which tend to have substantially larger balance sheets but are less active in the Australian interbank markets (Table 2.2).

The key dependent variable is a balanced panel of *loans outstanding* of length eight days or less over the 20 business days from Monday 8 September to Friday 3 October 2008, at the lender-borrower-day-market level. To construct this, we sum all (gross) loans from lender l to borrower b that occurred in market m and were open at the end of day d. Typically $m \in \{unsecured, secured\}$; in some instances $secured$ is separated into multiple markets by collateral type. If lender l never lent to borrower b in the sample or subsample analysed, the lb counterparty pair is excluded; if lender l lent to borrower b but not on day d in market m, loans outstanding for $lbdm$ is zero. We measure outstanding loans in millions of AUD, add one, then take the natural logarithm, because the raw distribution of activity across entities is highly skewed (discussed in the previous section; see Table 2.1).

[15] Accounts are assumed client accounts if the words 'nominee', 'custodian' or 'client', or any abbreviation of these, appear in the account name. Where multiple client accounts are owned by a single organization, those client accounts are grouped into a single 'client' entity.

Without taking logs, our results would likely reflect only the behaviour of a small number of highly active banks. To separately analyse the extensive margin, we also construct *participation*, which equals one if *loans outstanding* is positive and zero if *loans outstanding* is zero.

The key explanatory variables are collateral holdings *clt*, non-performing loans *NPL* and the TED spread *TED*. Collateral holdings and *NPL* are at the bank (i.e. borrower or lender) level and *TED* is at the day level. In some instances collateral holdings are split into measures of a certain collateral type (i.e. AGS or SGS). All are standardized to have zero mean and unit variance.

Collateral holdings *clt* measures the total face value of AGS and SGS that were held at both 1 September 2008 and 8 September 2008. Including only securities that were held at both dates helps to minimise the influence of high-frequency changes in holdings. Specifically, for each ISIN, which is the lowest level at which securities are identifiable, we take the minimum of the face value held at 1 September and at 8 September, and sum this across all AGS and SGS ISINs held by that bank (for the AGS holdings and SGS holdings measures in Section 2.3.3, we sum across only AGS ISINs or only SGS ISINs). We measure this in billions of AUD, add one, then take the natural logarithm. Because collateral holdings is an ex-ante measure, it is best interpreted as a soft constraint on repo borrowing. Banks could have acquired more collateral between the first week of September and the weeks in our sample, but it would have entailed transaction costs that were likely intensified by the tight liquidity conditions.

NPL measures the ratio of non-performing loans over total loans in percentage points, as at end 2007 or the closest available reporting date to end 2007. This is a common measure of counterparty risk in interbank markets, used by, for example, Cocco et al. (2009) and Afonso et al. (2011). Collateral holdings and *NPL* are left as missing values for client and state-government related entities, which removes them from some of the analysis.

TED measures the spread between three-month LIBOR based on the USD and the three-month Treasury bill rate in percentage points, lagged one day, or, if unavailable, from the most recent day prior to the previous day. The measure is lagged to account for the difference in Australian and US time zones.

Table 2.4 reports the means and standard deviations of the explanatory variables before standardisation. Figures 2.5 and 2.6 illustrate the histograms of *clt* and *NPL* before standardization. Both variables are roughly uniformly distributed aside from a mode at zero, without any clear outliers.

The sample includes 30 borrowers and 31 lenders with observations of *clt* and *NPL*; 42 lenders and 48 borrowers in total. In each market, there are typically about 20 involved at any point in time, and around 50 to 60 active counterparty pairs (Figure 2.7).

2.2.5 Empirical strategy

Our objective is to compare how borrowers' (lenders') counterparty risk and collateral availability determine activity in the repo and unsecured markets when market-wide stress arises. We achieve this by regressing borrowing (lending) in each market, and the difference in borrowing (lending) across markets, on an interaction between market-wide stress and ex-ante borrower (lender) characteristics. The idea is that following an unexpected increase in market stress, differences in risk characteristics and available collateral levels led to unanticipated differences in access to credit in the unsecured and repo markets. Similar identification strategies are adopted by, for example, much of the monetary policy transmission literature, some notable examples being Kashyap and Stein (2000) and Jiménez et al. (2014), both analysing how differences in predetermined balance-sheet characteristics lead to differences in banks' reaction to monetary policy changes.

Identification rests on an assumption that the measure of market stress is exogenous, i.e. it is not affected by the behaviour of borrowers and lenders in our sample. As discussed in Section 2.2.1, we have high confidence that conditions in Australian interbank markets had no material effects on the TED spread, owing to the sheer difference in size and global centrality between the US and Australian financial systems. This is indeed a key advantage of focusing on the Australian interbank market. To ensure exogeneity of the borrower characteristics we measure them at the start of the sample or earlier.

First we examine three 'individual' markets: repo, unsecured, and both grouped together as a joint sample. The explanatory variables of interest are the interactions between the market stress measure and the counterparty-characteristics:

$$X_b = [NPL_b,\ clt_b,\ NPL_b * clt_b].$$

To ensure coefficients on counterparty characteristics are not biased by endogenous counterparty selection by the heterogeneous borrowers and lenders, we include borrower-times-lender fixed effects. For example, the theoretical literature argues that monitoring incentives and diversification motives are important for interbank transactions (Rochet and Tirole 1996; Allen and Gale 2009; Freixas and

Rochet 2008), which implies that lenders choose their borrowers in similar (for monitoring) or in different (for risk diversification) businesses and geographical areas. Additionally, to focus on the difference in responses to stress *across* counterparties, we include day fixed effects. The regression equation is

$$loans\ outstanding_{lbd} = \alpha_{lb} + \alpha_d + ted_d * X_b\beta + \varepsilon_{lbd}. \tag{2.1}$$

Next we explicitly compare the difference between the repo and unsecured markets. The variables of interest are triple interactions between an indicator variable for whether the market is secured $\mathbb{1}_s$, the measure of market stress, and the counterparty-characteristics. Following the credit channel literature (e.g. Khwaja and Mian 2008; Jiménez et al. 2017), we saturate the regressions with fixed effects to control for unobserved variation; in our case lender-times-borrower-times-day fixed effects which isolate the difference between the two markets. The coefficients on these triple interactions determine whether, when market stress rose, the difference between repo and unsecured borrowing levels changed more for certain types of borrowers, i.e. whether some types of borrowers substituted between markets. The regression equation is

$$loans\ outstanding_{lbdm} = \alpha_{lbd} + \gamma\mathbb{1}_s + \phi\mathbb{1}_s * ted_d + \mathbb{1}_s * X_b\theta + \mathbb{1}_s * ted_d * X_b\beta + \varepsilon_{lbdm}. \tag{2.2}$$

We also repeat similar regressions with borrower characteristics replaced by lender characteristics, and with the dependent variable *participation* using a linear probability model. All regressions are clustered at the lender and borrower and day levels. We choose these levels of clustering because it is entirely plausible that residuals would be correlated within borrowers (and across lenders), within lenders (and across borrowers), and within days (across lenders and borrowers). For most regressions this sets the minimum number of clusters at 20 (the number of days in our sample), so in footnotes we also state whether the reported significance levels change when using error variance-covariance estimates that avoid having fewer than 30 clusters. For (2.2), we cluster at the borrower and lender levels, and for (2.1), we use White's standard errors, because there are fewer than 30 borrowers and lenders.

As a placebo test, we repeat the key regressions on the corresponding 2006 sample, using 2008 values for our key treatment variable, the TED spread, in line with the suggestion by Roberts and Whited (2013). All loan-related and bank-characteristic variables are constructed as described in Section 2.2.4, but using 2006 data. The sample also starts on 8 September, running for four weeks until 5 October (with 19 days owing to a public holiday in this period). This provides robustness against our results being driven by seasonal factors such as quarter-end or time-of-month effects.

2.3 Results

Here we analyse how activity in the repo and unsecured markets responds to an exogenous shock to financial-system stress. Aggregate activity displays markedly different responses in the two markets. Following the rise in the TED spread around the time of the Lehman Brothers default, the unsecured market remains relatively flat, whereas the repo market approximately triples in size, with the pickup in activity moving roughly in line with the TED spread (Figure 2.8). The repo-market expansion contrasts with the tightening observed in US repo markets against private collateral (Gorton and Metrick 2012a; Krishnamurthy et al. 2014) and is more in line with the stability observed in US and European repo markets against high quality securities (Copeland et al. 2014; Mancini et al. 2015). In the terminology of Dang et al. (2015), collateral in the Australian market remained information insensitive. Mancini et al. (2015) find that after the peak stress, volumes in European repo and unsecured markets became negatively correlated. Figure 2.8 displays a similar pattern; the cross-market correlation up until 16 September is 0.08 and afterward is -0.65.

2.3.1 Borrower characteristics

This section focuses on the change in composition of borrowers behind the aggregates in Figure 2.8. We treat the change in the TED spread as an exogenous treatment variable, and analyse how the response to the treatment varies across borrower characteristics and markets. As with the aggregates, the markets differ in their compositional response, with borrower NPL playing a stronger role in the unsecured market and borrower collateral holdings in the repo market.

Figures 2.9 to 2.11 explore in greater detail the market-wide negative correlations displayed in Figure 2.8. Each scatterpoint represents the borrowing of a bank on a given day in the repo and unsecured markets, after subtracting its average borrowing in that market across all days.[16] Only observations for banks that borrowed in each market at least once are retained. A positive relationship indicates that banks are spreading their fluctuating liquidity needs across both markets, while a negative relationship suggests that banks are substituting between the two markets, on any given day concentrating their borrowing in only one.

[16] For example, denoting bank i's borrowing in millions of AUD on day d in market $m \in \{s, u\}$ as b_d^{im}, and defining $B_d^{im} = \ln(b_d^{im} + 1)$, the scatter point for bank i on day 2 is

$$\left(B_2^{is} - \frac{1}{D} \sum_{d=1}^{D} B_d^{is}, \quad B_2^{iu} - \frac{1}{D} \sum_{d=1}^{D} B_d^{iu} \right).$$

The three figures each plot fitted lines for different subsamples of days and borrowers. The slopes are consistent with the following story.[17] First, on high-stress days banks face tighter borrowing constraints which generates greater cross-market substitution (Figure 2.9). Second, on high-stress days, constraints are more likely to bind for borrowers with high NPL (Figure 2.10). Third, of high NPL banks, those with higher levels of collateral have greater capacity to substitute into the repo market (Figure 2.11).

We next analyse these effects more rigorously using regression specifications 2.1 and 2.2. Table 2.5 reports the coefficient estimates for (2.1), applied to the unsecured market, the repo market, and both markets together.[18] Columns (a) and (b) show that when stress is higher, borrowing is negatively related to counterparty risk in the unsecured market, regardless of how much collateral the borrower holds. The effect size is economically meaningful, particularly given that marginal reductions in liquidity access could have substantial consequences for a liquidity-scarce bank. Consider the impact on two borrowers with a one standard deviation difference in *NPL* (around a quarter of the *NPL* range), following an increase in ted from 1.2 to 3.2 (the first week mean to the last week mean, a difference of 2.3 standard deviations). If each borrower initially had \$100 million in outstanding unsecured loans with some particular lender (the median nonzero value in the unsecured market), a coefficient of -0.06 estimates that the higher NPL borrower will reduce borrowing from that lender by about \$13 million more than the lower NPL borrower. This negative effect of NPL is qualitatively similar to findings for the US unsecured market during the crisis (Afonso et al. 2011).[19] In the Australian unsecured market lenders tend not to respond to counterparty risk with higher rates (discussed in Section 2.2.1), but the quantity responses in our results are in line with theory.[20] Models with symmetric information predict that riskier borrowers will pay higher rates and borrow less, compensating lenders for a higher probability of default (for example Bruche and Suarez 2010). Models of interbank markets with asymmetric information predict that banks can reduce lending in response to a higher proportion of high-risk borrowers in the market (Freixas and Holthausen 2004; Heider et al. 2015).

[17] Removing outliers tends to steepen each of the slopes.

[18] With heteroskedasticity-robust standard errors, which avoid using a small number of clusters, the significance levels of the following coefficients rise: the *TED * NPL* coefficients in columns (b), (c), (d), and (f), and the *TED * clt* coefficients in columns (d), (e) and (f).

[19] Cocco et al. (2009) also find a negative relationship between NPL and unsecured interbank borrowing in the Portuguese market using a sample from 1997 to 2001.

[20] Brassil and Nodari (2018) also find that Australian banks reacted to the crisis by limiting lending to certain borrowers.

In the repo market, the impact on borrower activity is more dependent on collateral holdings (Table 2.5, column (d)). When *NPL* and collateral holdings are not interacted (column (c)), *NPL* is estimated to have a significant negative effect, but in the more general specification (column (d)), *NPL* does not have a statistically significant effect on the mean borrower, but rather affects activity by varying the response to collateral holdings. Consider again an increase in *TED* from 1.2 to 3.2, and two borrowers each with mean *NPL* and a one standard deviation difference in collateral holdings (around a third of the *clt* range). If each borrower has secured loans outstanding with a particular lender of \$15 million (half the median nonnegative value in the repo market),[21] the borrower with higher collateral holdings is estimated to increase borrowing by \$3 million more than the other borrower. Now consider varying the high-collateral borrower's *NPL* to one standard deviation below or above the average. In the first case, the low *NPL* and high collateral holdings have an offsetting effect, leaving that bank's estimated repo borrowing the same as the borrower with mean *NPL* and lower collateral holdings. In the second case, the effects of high *NPL* and high collateral holdings compound, and borrowing is estimated to increase by \$10 million more than the borrower with mean *NPL* and lower collateral holdings.

In a model with ex-ante homogeneous banks, Heider and Hoerova (2009) show that following a liquidity shock, aggregate repo volume is increasing in borrowing banks' ex-ante bond holdings (which are homogeneous across borrowers). Intuitively, our estimates are consistent with a similar occurrence in the cross section – following a liquidity shock, banks with ex-ante larger collateral holdings borrow more in the repo market. Further, our results show that counterparty risk and collateral holdings have an interacting effect on repo borrowing, which is only observable in an empirical specification that can account for both.

Columns (e) and (f) of Table 2.5 report estimations of equation 2.1 on a sample that combines those used in the first four columns. Overall, *NPL* and *clt* are both statistically significant, demonstrating that the positive effect of *clt* is maintained using a broader sample, and that the repo market dynamics are significant for banks' overall liquidity access. A regression that for each borrower-lender-day observation sums the unsecured and repo quantities before taking logs gives similar estimates, with $ted * NPL$, $ted * clt$ and $ted * NPL * clt$ coefficients -0.073^{*}, 0.066^{*} and 0.030.

[21] Scaled down from the median to acknowledge the repo market growth between the first and last weeks.

In Table 2.6 we repeat the regressions in Table 2.5 but instead use the binary dependent variable *participation*, to analyse the extensive margin.[22] The results are qualitatively similar to Table 2.5, indicating that the response in the value of loans outstanding is at least partly driven by changes in the number of lenders that borrowers borrow from.[23] The estimates suggest that as *TED* rises, borrowers with higher collateral holdings are more capable of engaging additional borrowers when they need to. After the rise in *TED* from 1.2 to 3.2, a one standard deviation positive difference in collateral holdings (for the mean *NPL* borrower) is associated with borrowing from an additional 9 per cent of lenders, which roughly translates to borrowing from one to two additional lenders. A one standard deviation positive difference in collateral holdings *and NPL* is associated with borrowing from an additional 19 per cent of lenders. Column (f) indicates that across both markets, participation depends on borrower characteristics in a similar manner to that observed in the repo market.

Next we estimate (2.2) to directly analyse interactions between the repo and unsecured markets.[24] The borrower*lender*day fixed effects control for all unobservable factors that affect a borrower-lender pair's activity in both markets, so that we capture only how the *difference in borrowing between markets* is impacted by market and borrower characteristics. Columns (a) and (b) use the binary *participation* dependent variable in a linear probability model specification; columns (c) and (d) use *loans outstanding*.

The coefficients in columns (a) and (c) show that without controlling for interactions between *NPL* and collateral holdings, there is no statistically significant difference across markets. Permitting interactions reveals significant differences (columns (b) and (d)). The estimates indicate that borrowers with high *NPL* substitute into the repo market following the increase in market stress, demonstrating that the negative effect of *NPL* observed in columns (a) to (d) of Table 2.5 is significantly stronger in the unsecured market than the repo market. As expected from the previous regressions, the effect is even stronger for high *NPL* borrowers

[22]The extensive margin activity that we observe makes it difficult to analyse the intensive margin in isolation – i.e. condition the sample on *loans outstanding* being positive – because removing zero observations results in some singleton fixed-effect units, further reducing the sample size. Still, a lack of extensive margin activity would imply that effects are driven by the intensive margin.

[23]Using heteroskedasticity robust standard errors raises the significance level of the *TED* * *NPL* coefficients in columns (a) to (c) and raises the significance level of *TED* * *NPL* coefficients in columns (c) and (e).

[24]With clustering at the lender and borrower levels, which increases the minimum number of clusters from 20 to 30, the $\mathbb{1}_s$ * *TED* * *NPL* coefficients become not significant at 90 per cent, and the the $\mathbb{1}_s$ * *TED* * *clt* coefficient in column (b) and $\mathbb{1}_s$ * *TED* * *clt* * *NPL* coefficient in column (d) become significant at 90 per cent.

who also have access to larger amounts of collateral. The estimates in column (b) of Table 2.7 show that these effects are at least in part driven by the extensive margin, i.e. changes in the number of lenders that banks borrow from, potentially including borrowers entering and leaving the market completely.

Together, the results in Tables 2.5, 2.6 and 2.7 tell us that the cross-market substitution concluded by Mancini et al. (2015), based on correlations between market-wide volumes of activity, occurs more for some borrowers than others. The liquidity tightness for riskier borrowers in the unsecured market observed by Afonso et al. (2011) may not provide the full story, because if these borrowers had access to reliable repo collateral, their repo borrowing could have increased to offset the decline in unsecured borrowing. Also keep in mind that each of these regressions focuses on compositional effects within days. The fact that overall the repo market grew, while the unsecured market remained roughly the same size (Figure 2.8), indicates that these compositional effects were on top of a market-wide shift to repo funding, and therefore substitutions into the repo market, by borrowers that were able to, could have more than offset any decline in unsecured borrowing.

2.3.2 Lender characteristics

In this section we test whether, when market-wide stress emerges, the composition of lenders changes within or across markets. A reduction in lending would be consistent with liquidity hoarding, whereby banks reduce lending to build up liquidity buffers and protect against potential future adverse shocks, such as further disintegration of interbank markets (Acharya and Skeie 2011; Gale and Yorulmazer 2013). Still, another potential explanation is that lenders could be reacting to a decline in their own borrowing capacity. In this case, we would expect the estimates to look similar to those for the borrower-characteristic regressions.

Tables 2.8 and 2.9 present the coefficients from estimating equations 2.1 and 2.2 with lender characteristics in place of borrower characteristics. Afonso et al. (2011) find that riskier banks react to market-wide stress by increasing the number of counterparties they lend to, consistent with signalling to the market that they are not under liquidity distress. We find that banks with high *NPL* and high *clt* increase unsecured lending (and repo lending although this is not statistically significant), consistent with these banks signalling to the unsecured market that despite appearing risky, they have no liquidity shortages (remember that these banks increased their repo borrowing over the sample period). Regressions of *participation* (unreported) estimate the corresponding coefficients to be positive and significant at 90 per cent, demonstrating that the increase in lenders was not confined to pre-existing borrowers, which supports this interpretation. The coefficients reported in columns (a) and (c) of Table 2.9 indicate that banks' repo lending relative to unsecured lending is increasing in collateral holdings. This could be driven by low collateral lenders increasing lending in the unsecured market, which is consistent with the negative *TED * clt* coefficients in columns (a) and (b) of Table 2.8. Still, these results disappear when permitting collateral holdings and *NPL* to interact (columns (b) and (d)), which is our preferred specification.

2.3.3 Collateral type in the repo market

A common theme across the theoretical and empirical repo-market literature is that the type of collateral can be a key determinant of repo-market behaviour.[25] These studies tend to distinguish between low- and high-quality collateral; however, this distinction is less relevant for the Australian market, which is primarily collateralised by high quality collateral. Still, Bartolini et al. (2010) demonstrate that liquidity rankings can exist across security types within the category that would be considered high quality, which we analyse in this section. We find differences in the market-wide behaviour of AGS and SGS repos, as well as in the compositional changes across borrowers.

The expansion of the repo market after the Lehman Brothers default was entirely driven by an expansion of loans against SGS, while the total value of repos against AGS remained flat (Figure 2.12). Around the same time that SGS repo activity increased, interest rates on AGS repos noticeably dropped, while rates on SGS repos (and other-collateral repos) remained relatively flat (Figure 2.13, top panel). The drop in rates on AGS repos was not confined to a small number of counterparty pairs (Figure 2.13, bottom panel). Also note that the Australian Government had a very low level of debt (in mid 2009 the Government's debt was less than the value of its financial assets), and the face value of SGS on issue was higher than of AGS. Together, these facts are highly suggestive that as demand for liquidity grew and was absorbed by the repo market, available AGS was insufficient to meet this demand, which pushed the market into the second-best collateral type SGS. Garvin (2018) shows that the proportion of repos collateralized by SGS gradually declined in subsequent years, which was also when the Australian Government debt was growing.

This behaviour corresponds closely to the findings of Bartolini et al. (2010), who show that during (non-crisis) periods of heightened liquidity demand in the US, the spread between Treasury repos and repos against collateral issued by government-sponsored agencies increased, driven mainly by declines the in rates on Treasury

[25]For example, Dang et al. 2015. The introduction cites several papers.

repos. Demand for and supply of collateral types has also been shown to drive repo rates in other contexts. 'Special' repos, in which the cash lender seeks a specific security as collateral, for example to cover a short sale, typically have lower rates (Duffie 1996). Also, D'Amico et al. (2014) document a positive relationship between Treasuries' market supply, with fluctuations driven by changes in the Fed's holdings, and rates on repos against those securities.

To investigate whether the change in borrower composition across markets differed by collateral type, we re-estimate (2.1) after separating the AGS and SGS repo markets, and as explanatory variables use only collateral holdings that correspond to that market. Columns (a) and (c) of Figure 2.10 report the results for the AGS and SGS repo markets, respectively, and columns (b) and (d) report results for the unsecured market using the same explanatory variables as in columns (a) and (c).[26]

Intuitively, as *TED* rises, borrowers increase borrowing in the repo market for which they hold collateral. However, a noticeable difference across the AGS and SGS markets is that the interaction between *NPL* and collateral holdings is only significant for the AGS market. For riskier borrowers, lenders appear to perceive AGS collateral as providing better protection against counterparty risk than SGS collateral. This can also in part explain the heightened demand for holding AGS collateral reflected in the behaviour of AGS repo rates (Figure 2.13).

Figures 2.14 and 2.15 graphically portray the information in the Table 2.10 regressions, for the AGS and SGS repo markets respectively. Each panel represents a subset of borrowers, depending on whether their collateral holdings (i.e. *AGS* or *SGS*) and their *NPL* is above or below the median value. First, each bank's borrowing is converted to a weekly index value, representing their total borrowing that week (i.e. loans outstanding on a typical night in dollar values) as a proportion of their average weekly borrowing in that market across the sample. Then, for each panel in each figure, these index values are averaged across borrowers, so each borrower is represented equally. The plots convey similar conclusions to Section 2.3.1 – high *NPL* borrowers reduce unsecured borrowing, and high collateral borrowers increase repo borrowing against that collateral type. For both AGS and SGS, the largest disparity in the final week is for high collateral and high *NPL* borrowers, with repo borrowing around 25 per cent higher than its sample average, compared with unsecured borrowing around 50 per cent below its sample

[26]Using heteroskedascticity-robust standard errors mainly raises the significance level of most of the significant coefficients, and two of the coefficients in column (b) become significant at 95 per cent.

average. It also stands out that the largest increase in either chart is high *SGS* low *NPL* borrowers' SGS repo borrowing. This conforms with the story that while the SGS repo market expanded to absorb the overall heightened liquidity demand, it was less accessible for high *NPL* borrowers.

To explicitly examine difference in behaviour across the AGS and SGS repo markets, in Table 2.11 we re-estimate (2.2) after redefining the market level m to three different definitions: $m \in \{unsecured, AGS\}$ (column (a)), $m \in \{unsecured, SGS\}$ (column (b)) and $m \in \{AGS, SGS\}$ (columns (c) and (d)). For each specification the market indicator $\mathbb{1}_s$ is also replaced with an indicator of a particular level of m (specified in the column headings).[27] Most evident is that risky borrowers with high *AGS* tend to shift into the AGS repo market from the unsecured and SGS repo markets, supporting our conclusion that lenders perceived AGS collateral as better protection against counterparty risk than SGS. In contrast, we do not observe a shift by risky borrowers with high *SGS* into the SGS repo market (columns (a) and (d)).

In Table 2.12 we analyse lender characteristics by repeating the regressions from Table 2.10 after replacing borrower characteristics with lender characteristics.[28] High *NPL* and high *SGS* lenders increase lending in the unsecured market, indicating that the significant positive coefficient in column (b) of Table 2.8 is driven by holders of *SGS*. This is in line with the signalling interpretation, because banks with high AGS holdings are less likely to need to signal. The table does not show any other significant effects.

2.3.4 Robustness checks

In this section we rule out factors that could potentially confound our conclusions. First, we run a set of placebo regressions, repeating the analysis in Section 2.3.1 on 2006 data, when markets were calm, using the treatment variable *TED* from our 2008 sample (following the suggestion of Roberts and Whited (2013)). Second, we show that neither bank domicile nor size is driving the results that we attribute to counterparty risk. Third, we show that the main coefficient of interest is largely insensitive to the degree of fixed effects adopted.

A placebo test on 2006 data addresses two potential concerns. First, it tests whether our results are being driven by time of month, time of quarter, or time

[27] With clustering at the borrower and lender levels, the significant coefficients in column (a) become significant at 95 per cent and 90 per cent, respectively.

[28] With heteroskedasticity robust standard errors, four coefficients become significant at higher levels.

of year effects. It is possible that the extreme volatility in the TED spread in September 2008 coincided with patterns in interbank markets that occur on a regular basis, and if so, our regressions would suffer from omitted variable bias by not controlling for these seasonal factors. Second, the placebo test performs the typical function in the non-experimental literature – ensuring that the results are not being driven by random variability.

Figure 2.16 plots aggregate lending in the repo and unsecured markets for a four week sample starting 8 September 2006, with the 2006 and 2008 TED spreads. The contrast between the TED spreads – the 2006 TED appears as a flat line at this scale – highlights the extremity of the volatility in September 2008. The 2006 unsecured lending series picks up moderately in the second half of the sample, whereas the 2008 unsecured lending series (in Figure 2.8) if anything declines. The 2006 repo lending series also picks up moderately in the second half of the sample, but by a much smaller proportion and at different times to the 2008 repo lending series. In 2006 it remains around half the size of the unsecured market, and displays little movement when the 2008 TED first picks up after the Lehman Brothers default. Overall these patterns in 2006 indicate that seasonal factors could be affecting our 2008 sample, but not driving our results.

The placebo regressions confirm this conclusion. Using 2006 data for all variables except *TED*, which is taken from 2008, we repeat the regressions in Table 2.5 and Table 2.7, and find only one of the coefficients on time-varying variables significant at the 90 per cent level (Tables 2.13 and 2.14).

Many studies have found relationships between bank size and variables relating to activity and counterparty risk (most relevantly Afonso et al. 2011). We do not expect these relationships to be strong in our sample, in part because the major domestic banks are the most dominant in the Australian financial system, but the foreign banks tend to be far larger. In our sample, the largest Australian entity has 570 billion AUD assets, whereas the largest foreign entity has around 4.2 trillion AUD assets (Table 2.2). The Australian banks also tend to have lower *NPL* than the foreign banks, in line with much of the financial stress in Australia having been imported from the major global financial centres.

To ensure that neither bank size nor domicile are confounding the relationships we attribute to counterparty risk, we repeat the estimates in Tables 2.5 and Table 2.7 after replacing *NPL* with either *size* or $\mathbb{1}$*(foreign)*. The variable *size* is the natural logarithm of the bank's balance sheet size (i.e. asset value) measured in AUD trillions, taken at the same time as the measure of that bank's *NPL*, and $\mathbb{1}$*(foreign)* is a dummy indicating whether the bank is not Australian. None of the coefficients relating to size or domicile that are interacted with *TED* are statistically significant (Tables 2.15 to 2.18).

Next we re-estimate (2.2) with every possible level of fixed effects, focusing on the primary coefficient of interest, which represents the differential effect across markets of the interaction between *NPL*, collateral holdings and *TED*. As we vary the fixed effects, we also vary the number controls to ensure that all valid lower-level interactions are included. Tables 2.19 and 2.20 report the estimates, which are remarkably stable. Our chosen specification is in the fourth last column. With no fixed effects, the specifications have an R-squared around three per cent. The largest possible set of fixed effects is borrower*lender*day and market*borrower*lender and market*lender*day (leaving out market*borrower*day because it is the level of our explanatory variable of interest), which gives an R-squared around 70 per cent. Despite this large difference in the explained variance, the coefficients of interest in both tables vary by at most 0.002, and 23 of the 24 estimates are statistically significant at 95 per cent (or more), the other being statistically significant at 90 per cent.

2.4 Conclusions

The failure of Lehman Brothers triggered a global financial crisis characterized by disruptions to wholesale funding liquidity around the world. In bank-dominated economies, interbank markets took center stage. Despite the fact that, during the 2008 global financial crisis, the repo (secured) interbank market became more important than the unsecured market, interbank repo transactions have not been analysed at the same level of granularity as unsecured markets due to a lack of comprehensive transaction-level repo data. We fill this void in the literature and, moreover, analyse how the two sides of interbank funding liquidity markets – unsecured and secured (i.e. repo) – react and interact in response to strong financial shocks.

Australia provides an ideal setting for empirical identification as: (i) it has supervisory, comprehensive transaction-level (i.e. borrower-lender-day-market-collateral level) data for both the repo and unsecured interbank markets; and (ii) the 2008 global financial crisis was largely exogenous to Australia, having not experienced a real estate crash. Transaction-level data are necessary to disentangle borrower (counterparty) risk from lender (e.g. liquidity hoarding) motives, as interbank markets are characterized by endogenous matching between borrowers and lenders.

We find that financial stress (proxied by the US Ted spread) leads to an expansion of the repo market relative to the unsecured market, and that banks' relative activity in each market depends on borrower (more than lender) balance-sheet strength and high-quality collateral holdings. Specifically, riskier banks reduce borrowing in the unsecured market, and banks with high-quality collateral increase borrowing in the repo market. While the repo-market expansion is almost entirely driven by the second-best (but still high-quality) collateral – consistent with a demand-driven scarcity of the first-best collateral, indicated by its repo rates falling around 100 basis points relative to second-best collateral – there is relative market segmentation depending on banks' ex-ante type of collateral holdings. Indeed, the strongest substitution from unsecured to secured markets is by risky (borrower) banks with plentiful first-best collateral.

We contribute to the academic literature by revealing the interactions between the two markets, which is heterogeneous across banks and collateral types, and thereby help to provide a holistic understanding of interbank markets and to discriminate among different theories about their functioning. In particular, we show that only analysing the unsecured market can lead to misleading conclusions, as repo markets can absorb liquidity demand unmet in the unsecured market, and, provided banks have sufficient collateral, risky borrowers can offset a reduction of unsecured borrowing with an increase in repo borrowing. Importantly, these dynamics can be affected by relative availability of different forms of high-quality collateral. In addition, our paper isolates the effect of collateral from that of infrastructure by directly comparing repo and unsecured markets that operate through the same market structure. We show that the two markets behaved differently in aggregate and in composition, demonstrating that the collateralization itself is a key determinant of market functioning.

Figure 2.1: Interbank Stress Measures 2008

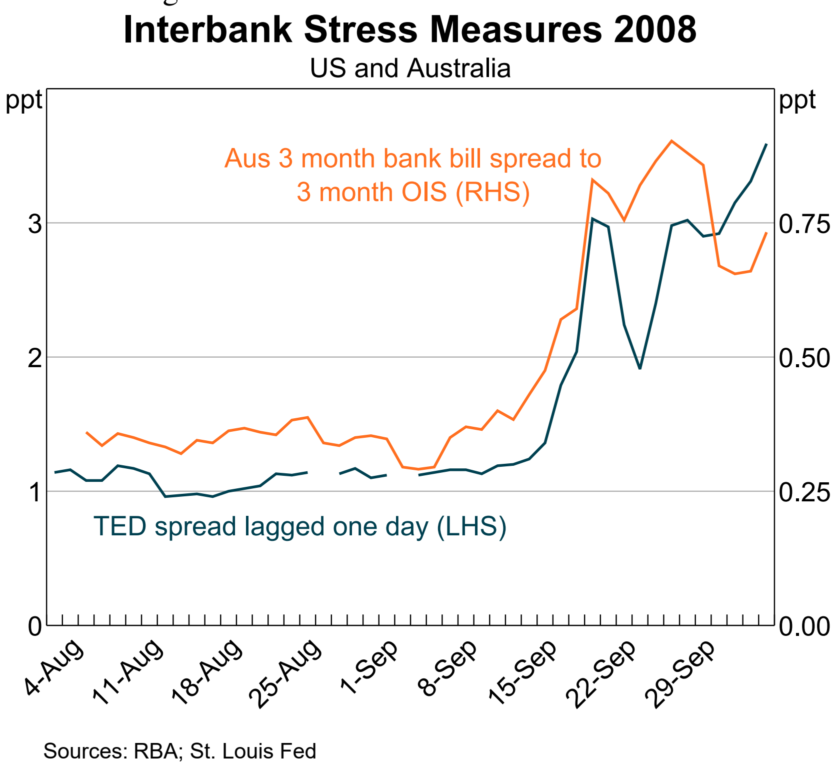


Figure 2.2: Banks' Funding Composition 2008

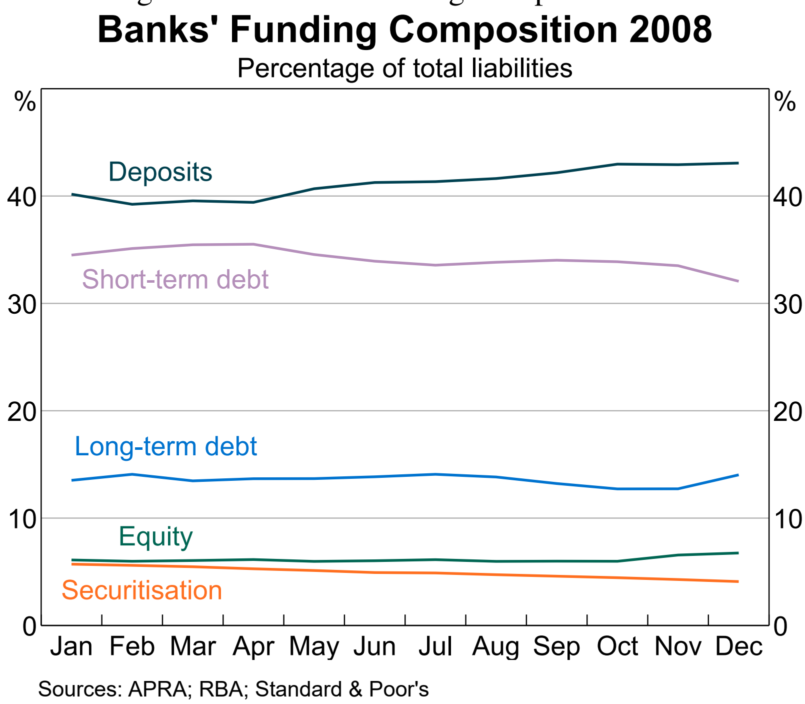


Figure 2.3: Banks' Bond Issuance 2008

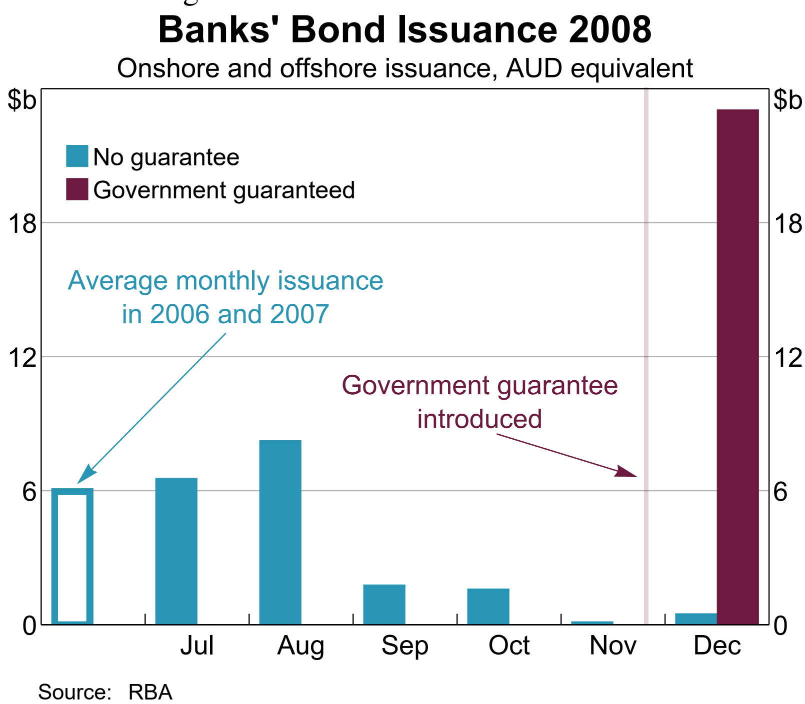


Figure 2.4: Open Market Operations and ESAs

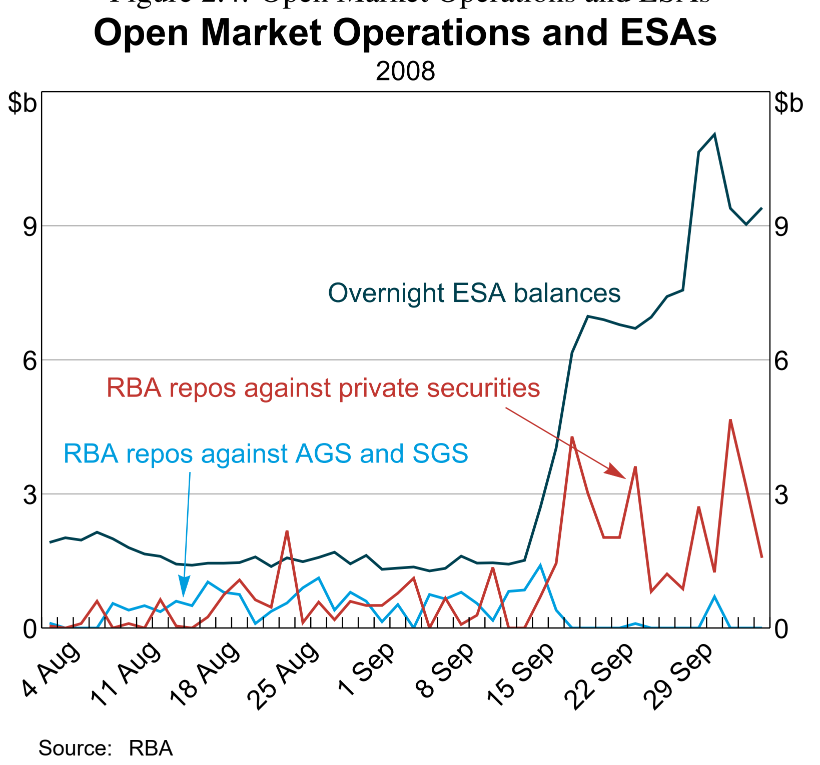


Figure 2.5: NPL Histogram

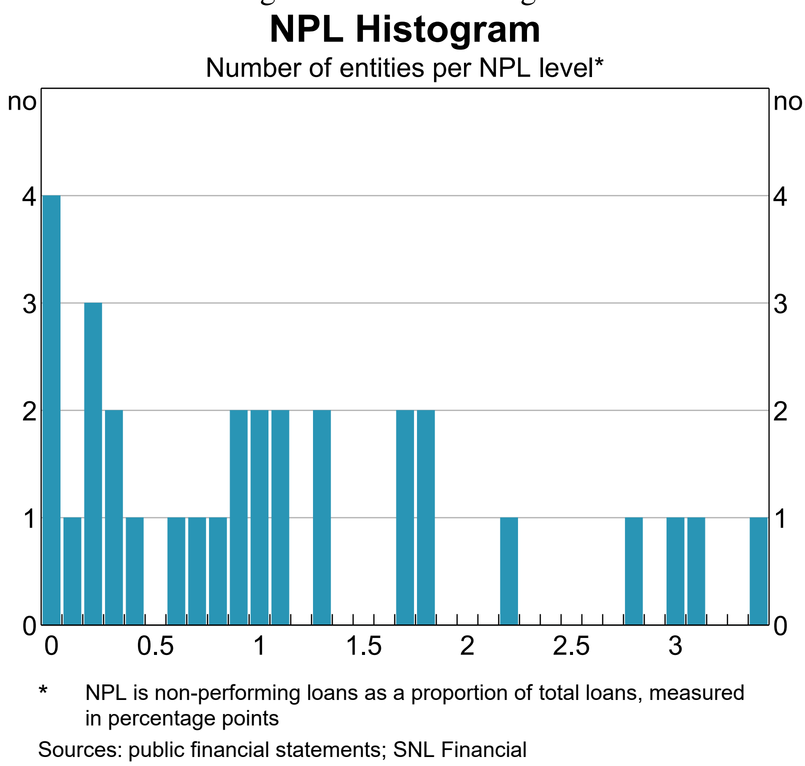
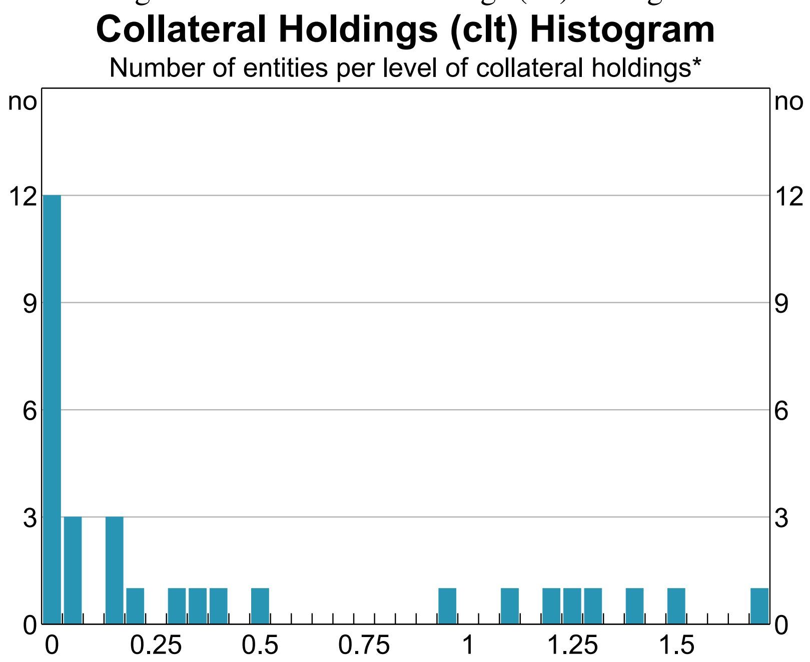


Figure 2.6: Collateral Holdings (clt) Histogram



* Collateral holdings measured as face value of AGS and SGS held at start of sample, in AUD billions plus one logged

Source: ASX

Figure 2.7: Numbr of Active Entities Each Day

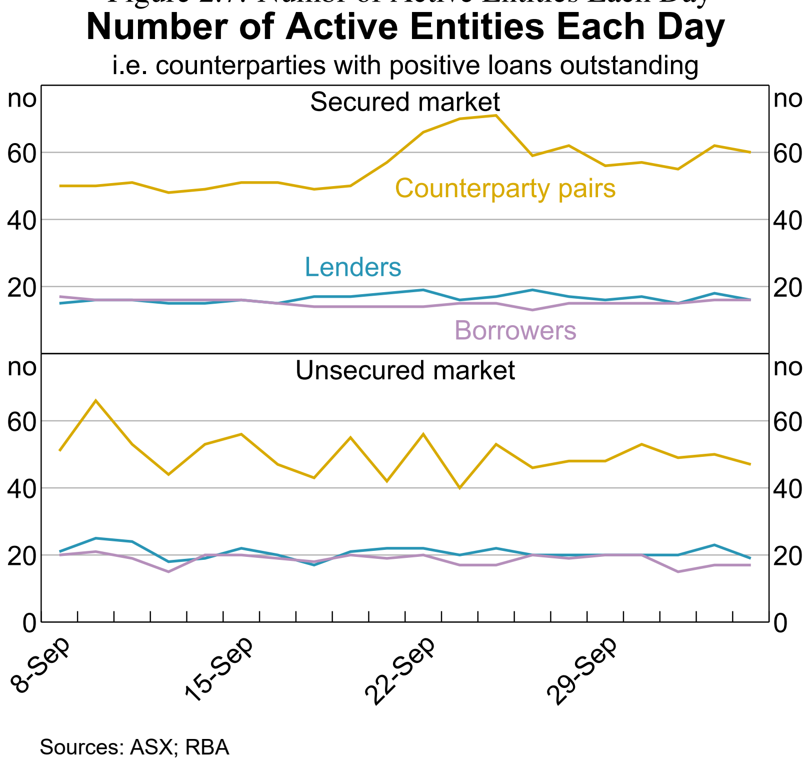


Figure 2.8: Loans Outstanding by market and TED Spread

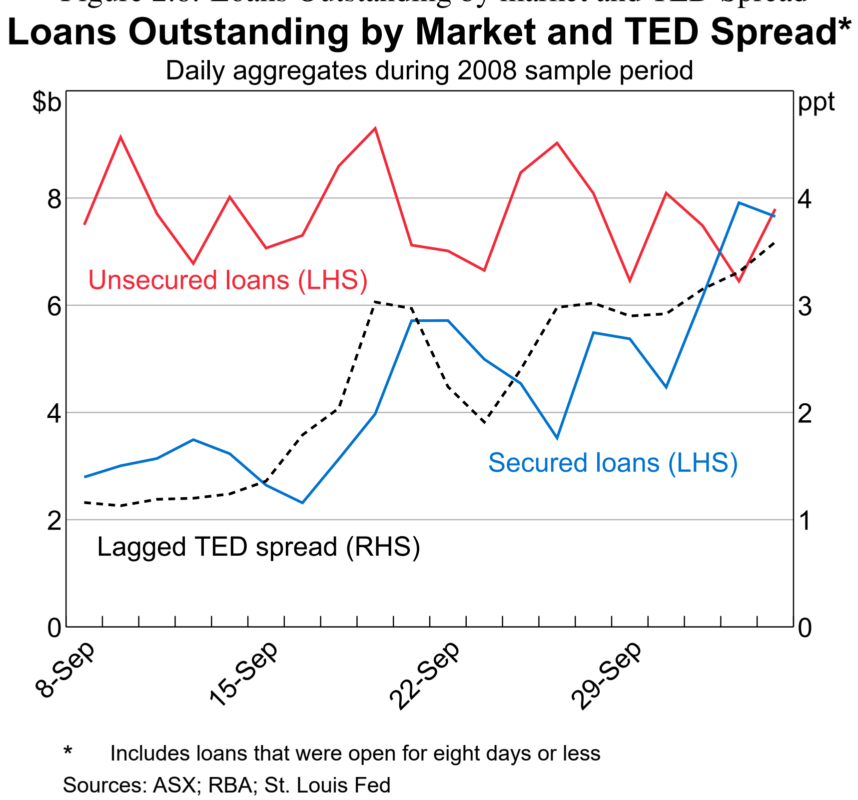
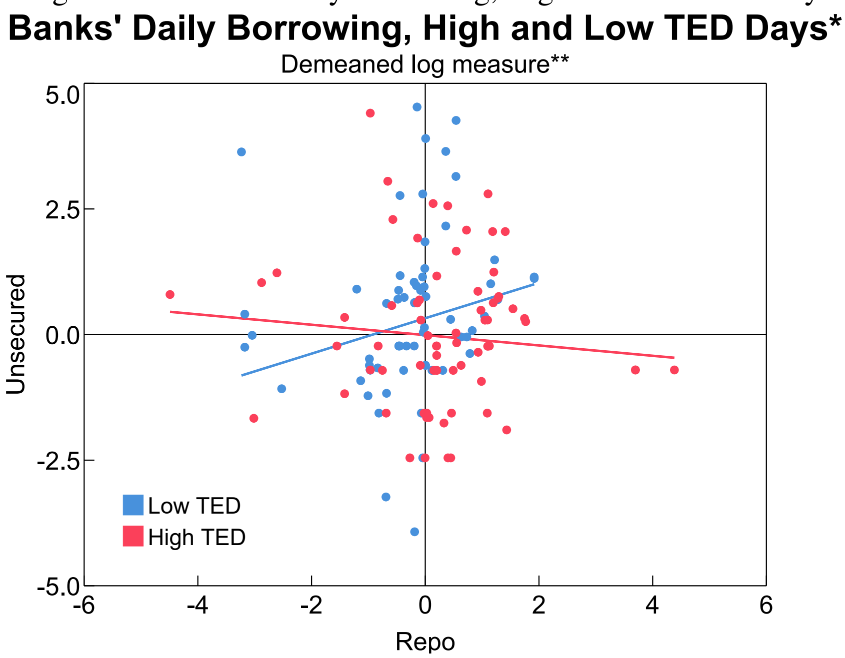


Figure 2.9: Banks' Daily Borrowing, High and Low TED Days

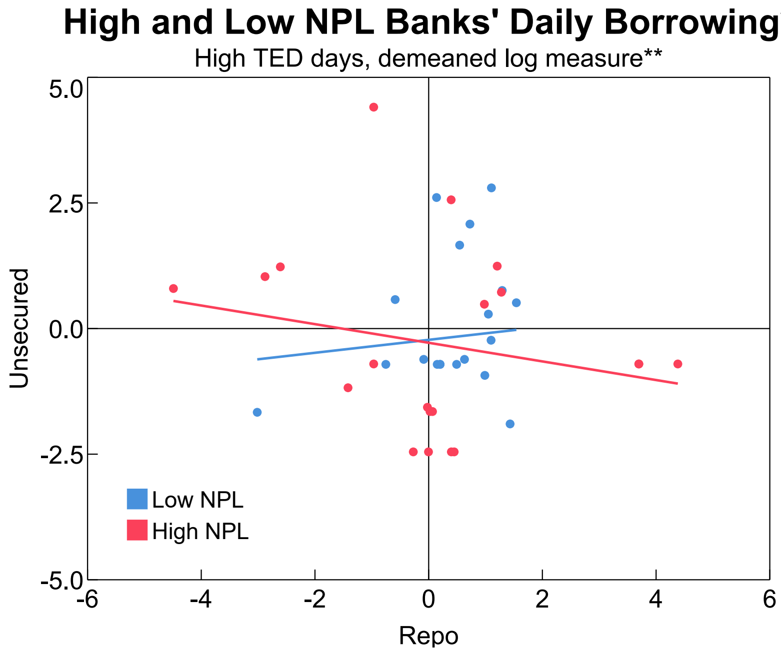


* High and low refer to top and bottom quartiles. Only borrowers with some activity in both markets included.

** Natural logarithm of borrower-day-market level observation measured in $m plus one, with borrower-market mean subtracted

Sources: ASX; Authors' calculations; RBA

Figure 2.10: High and Low NPL Banks' Daily Borrowing

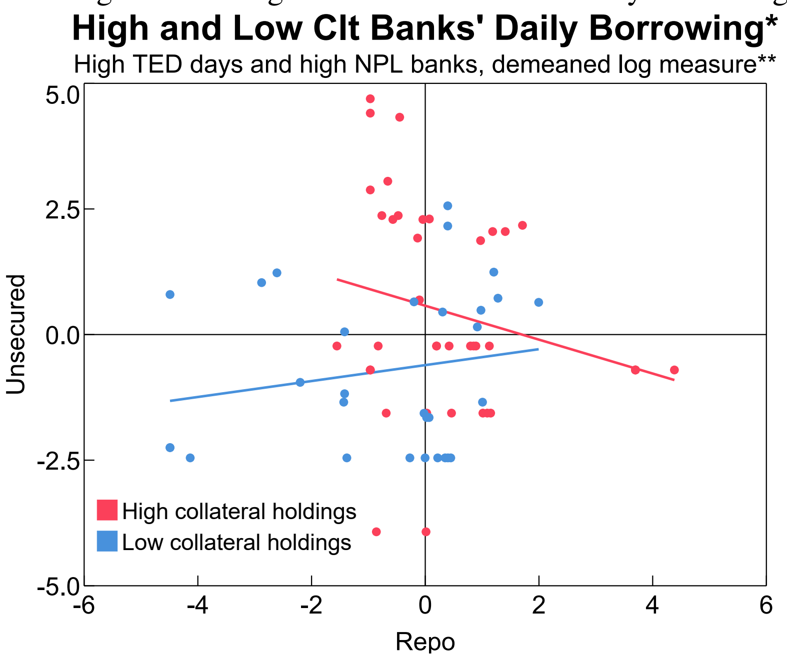


* High and low refer to top and bottom quartiles. Only borrowers with some activity in both markets included.

** Natural logarithm of borrower-day-market level observation measured in $m plus one, with borrower-market mean subtracted

Sources: ASX; Authors' calculations; RBA

Figure 2.11: High and Low Clt Banks' Daily Borrowing

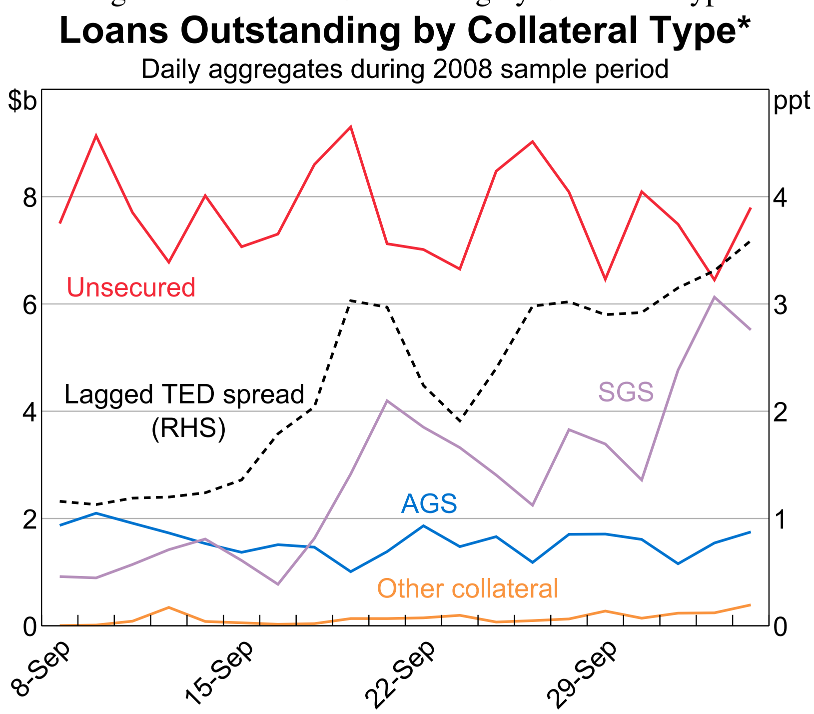


* High and low refer to above and below the median. Only borrowers with some activity in both markets included.

** Natural logarithm of borrower-day-market level observation measured in $m plus one, with borrower-market mean subtracted

Sources: ASX; Authors' calculations; RBA

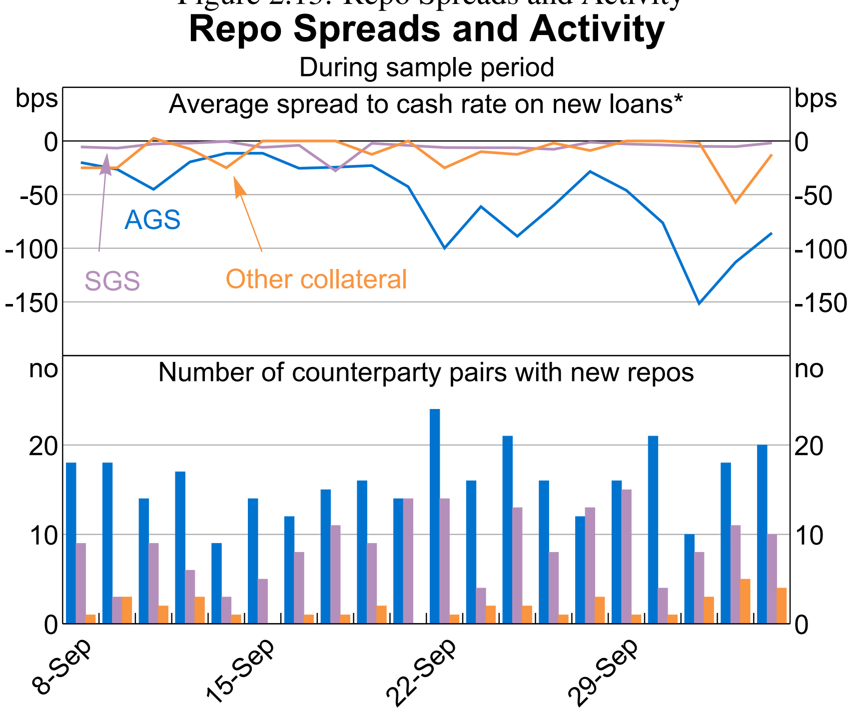
Figure 2.12: Loans Outstanding by Collateral Type



* Includes loans that were open for eight days or less

Sources: ASX; RBA; St. Louis Fed

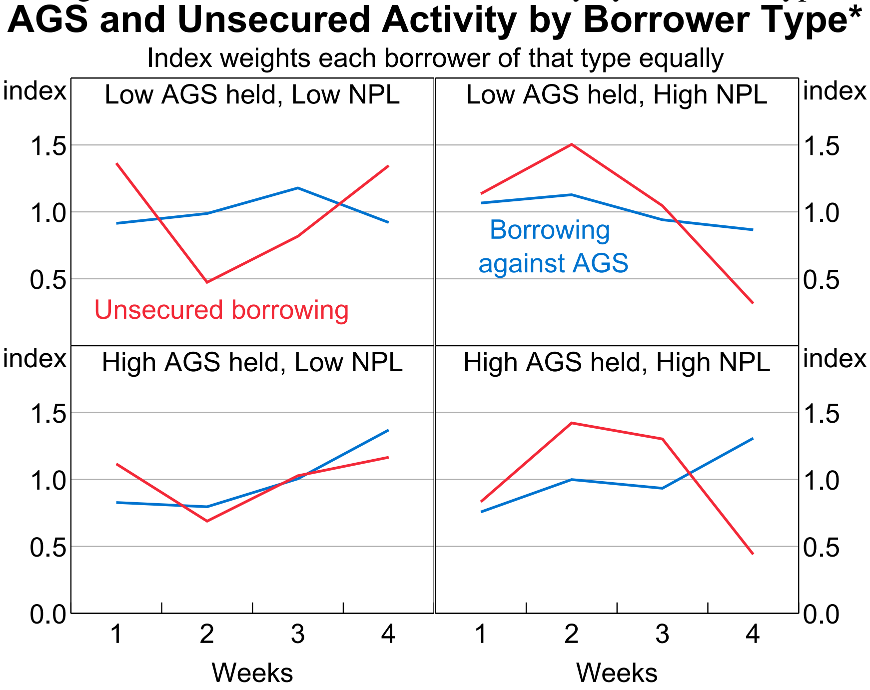
Figure 2.13: Repo Spreads and Activity



* Each counterparty pair weighted equally; loans within a pair are value weighted

Sources: ASX; RBA

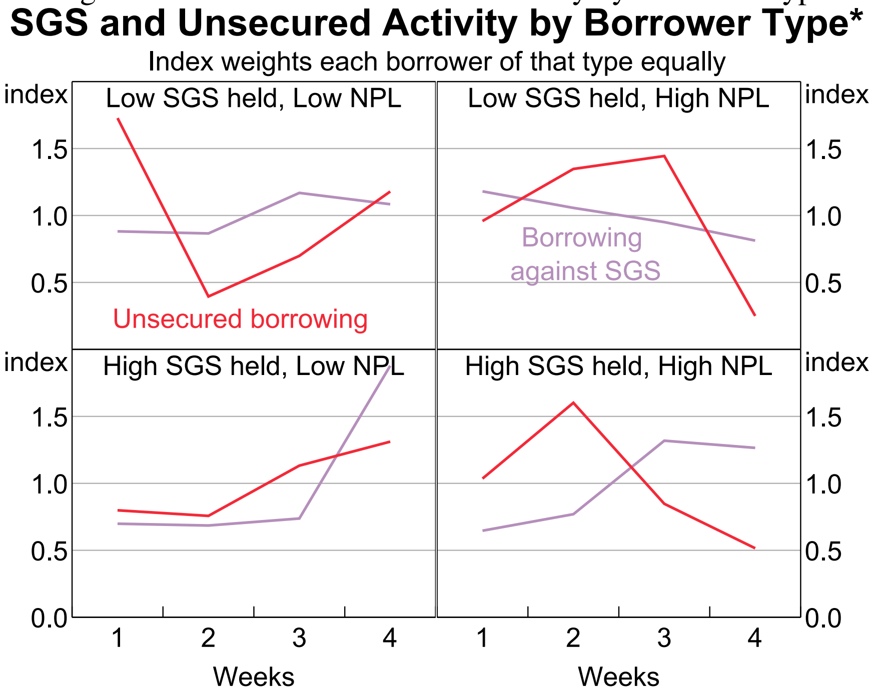
Figure 2.14: AGS and Unsecured Activity by Borrower Type



* High and low refer to above and below median

Sources: ASX; Authors' calculations; RBA

Figure 2.15: SGS and Unsecured Activity by Borrower Type



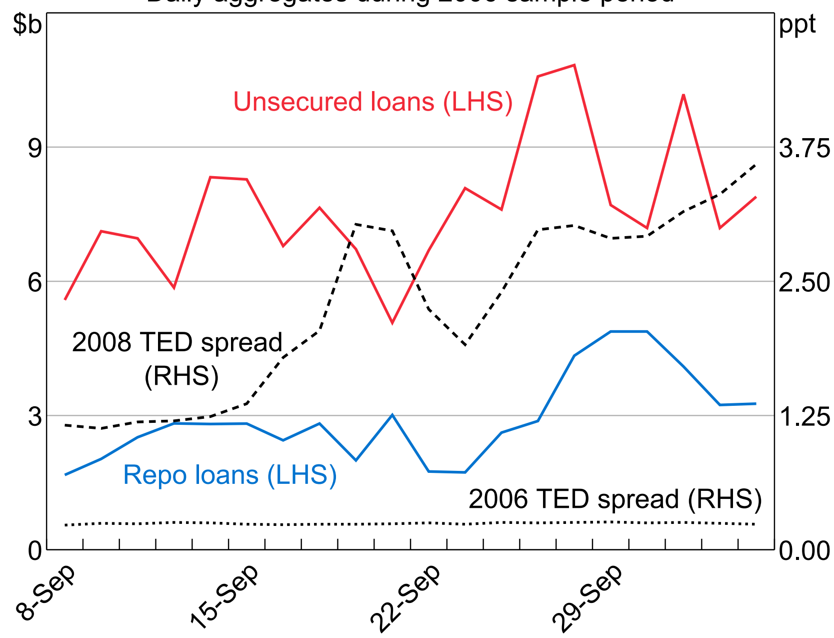
* High and low refer to above and below the median.

Sources: ASX; Authors' calculations; RBA

Figure 2.16: 2006 Loans Outstanding and 2008 TED Spread

2006 Loans Outstanding and 2008 TED Spread*

Daily aggregates during 2006 sample period



* Includes loans that were open for eight days or less

Sources: ASX; RBA; St. Louis Fed

Table 2.1:
Summary Statistics at the Loan Level

	Count		25	Median	Mean	75	99	Std Dev
Secured								
All	797	Principal ($mil)	7.58	22.6	44.53	50.06	410.86	77.37
		Spread (ppts)	−0.3	−0.1	−0.33	0.00	0.05	0.63
		Length (days)	2	4	4.25	7	8	2.46
AGS	444	Principal	5.9	20.38	34.12	36.6	274.87	65.55
		Spread	−0.60	−0.20	−0.55	−0.05	0.05	0.76
		Length	1	3	3.93	7	8	2.51
SGS	294	Principal	12.12	32.59	63.2	74.57	457.23	94.43
		Spread	−0.06	0.00	−0.04	0.00	0.05	0.15
		Length	3	5	4.87	7	8	2.3
Unsecured								
All	793	Principal	40	100	144.14	200	779.76	160.14
		Length	1	1	2.18	3	8	1.71

*Includes all loans that were open at some point between 8 September and 3 October. Spread measures the spread to the unsecured rate, i.e. to the target policy rate. Length measures the days between the first and last transaction in the loan.

Table 2.2:
Counterparty Characteristics

	Borrowers					Lenders				
	Secured		Unsecured		All	Secured		Unsecured		All
	Aus.	For.	Aus.	For.		Aus.	For.	Aus.	For.	
Count	7	8	8	21	30	6	11	8	22	31
Avg. daily loans (mil)										
Min	4	4	1	0		2	0	5	0	
Med	12	6	21	10	8	17	6	17	11	7
Max	82	14	51	39		51	41	59	44	
Assets (bil)										
Min	92	480	20	138		126	480	20	43	
Med	378	2037	257	1779	942	385	2083	257	1747	950
Max	574	4173	574	4173		574	4173	574	4173	
AGS face value (bil)										
Min	0.02	0	0	0		0.04	0	0	0	
Med	0.07	0.02	0.13	0	0.02	0.13	0.02	0.13	0	0.01
Max	1.09	1.26	1.09	1.26		1.09	1.26	1.09	1.26	
SGS face value (bil)										
Min	0.01	0	0.01	0		0.01	0	0.01	0	
Med	1.55	0.38	1.83	0.05	0.13	1.83	0.26	1.83	0.03	0.05
Max	4.4	2.3	4.4	2.3		4.4	2.3	4.4	2.3	

Average daily loans is the mean of teh *loans outstanding* dependent variable across the sample. Assets measures the book value of the entity's balance sheet at end December or the closest available reporting date, in AUD. AGS and SGS measure the entity's holdings of AGS and SGS in the first week of September 2008. Each column refers to a different subset of entities.

Table 2.3:
Summary Statistics for Sample of Loans Outstanding, in Millions of Dollars

		Count	25%	Median	Mean	75%	99%	Std. Dev.
Secured	incl. zeros	8120	0	0	10.99	0	205.78	78.51
	excl. zeros	1124	10.2	29.37	79.42	69.66	927.96	197.8
Unsecured	incl. zeros	8120	0	0	18.97	0	400	77.88
	excl. zeros	1000	40	100	154.06	210	778.22	168.72

Loans outstanding – our main dependent variable – is at the borrower-lender-day-market level. It measures the gross value of loans outstanding from that lender to that borrower on that night in that market.

Table 2.4:
Summary Statistics for Explanatory Variables Pre Standardisation

		Borrowers				Lenders			
	TED	NPL	AGS	SGS	clt	NPL	AGS	SGS	clt
Mean	2.28	1.07	0.13	0.38	0.44	1.19	0.12	0.36	0.42
Std. Dev.	0.85	0.94	0.23	0.51	0.57	0.97	0.23	0.51	0.57

TED is the US TED spread lagged one day for the sample 8 September 2008 to 3 October 2008, measured in percentage points. *NPL* is the entity's non-performing loans as a proportion of total loans, measured in percentage points at end 2007 or the closest available reporting date. *AGS* and *SGS* are the face value of that entity's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. *clt* is sum of AGS and SGS holdings measured in the same way.

Table 2.5:
Loans Outstanding Regressed on Borrower Characteristics and TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * NPL	−0.064***	−0.079*	−0.115**	−0.071	−0.081***	−0.067*
	(0.02)	(0.04)	(0.05)	(0.04)	(0.02)	(0.03)
TED * clt	0.037	0.021	0.039	0.102**	0.045	0.062**
	(0.05)	(0.05)	(0.06)	(0.04)	(0.04)	(0.03)
TED * NPL * clt		−0.028		0.107**		0.029
		(0.04)		(0.04)		(0.04)
fixed effects	borrower x lender and day					
N	5 900	5 900	3 080	3 080	8 980	8 980
R^2	0.191	0.191	0.363	0.364	0.224	0.224

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Standard errors are clustered at the lender and borrower and day levels.

Table 2.6:
Participation Regressed on Borrower Characteristics and TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * NPL	–0.016**	–0.016	–0.019	–0.001	–0.017***	–0.008
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
TED * clt	0.003	0.003	0.015	0.040***	0.010	0.020***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
TED * NPL * clt		0.000		0.041***		0.018**
		(0.01)		(0.01)		(0.01)
fixed effects	borrower x lender and day					
N	5 900	5 900	3 080	3 080	8 980	8 980
R^2	0.158	0.158	0.256	0.259	0.193	0.193

*p<0.1, **p<0.05, ***p<0.01. The binary dependent variable is *participation* at the lender-borrower-day-market level, equal to one if *loans outstanding* is non-zero and zero otherwise, from 8 September 2008 to 3 October 2008. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Estimates are derived using OLS in a linear probability model. Standard errors are clustered at the lender and borrower and day levels.

Table 2.7:
Participation and Loans-Outstanding Differentials Across Repo and Unsecured Markets, Regressed on Borrower Characteristics and TED

	(a) Participation	(b) Participation	(c) Loans	(d) Loans
$\mathbb{1}_s$ * TED	0.013	0.019	0.060	0.078
	(0.01)	(0.01)	(0.05)	(0.05)
$\mathbb{1}_s$ * TED * NPL	0.007	0.014**	0.014	0.039**
	(0.01)	(0.01)	(0.02)	(0.02)
$\mathbb{1}_s$ * TED * clt	0.007	0.016**	0.001	0.029
	(0.01)	(0.01)	(0.03)	(0.03)
$\mathbb{1}_s$ * TED * clt * NPL		0.016**		0.051***
		(0.01)		(0.01)
time-invariant interactions		yes		
fixed effects		borrower x lender x day		
N	15 560	15 560	15 560	15 560
R^2	0.504	0.505	0.531	0.533

*p<0.1, **p<0.05, ***p<0.01. The dependent variable in columns (c) and (d) is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. The dependent variable in columns (a) and (b) is *participation*, equal to one if *loans outstanding* is positive and zero otherwise (with coefficients estimated using OLS in a linear probability model). Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. All valid interactions between $\mathbb{1}_s$, *NPL* and *clt* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.8:
Loans Outstanding Regressed on Lender Characteristics and TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * NPL	−0.025	0.034	−0.033*	0.006	−0.032	0.015
	(0.05)	(0.06)	(0.02)	(0.03)	(0.03)	(0.04)
TED * clt	−0.148*	−0.008	−0.005	0.115	−0.081	0.042
	(0.08)	(0.07)	(0.08)	(0.08)	(0.07)	(0.03)
TED * NPL * clt		0.217**		0.170		0.182**
		(0.10)		(0.11)		(0.07)
fixed effects	borrower x lender and day					
N	5 400	5 400	3 080	3 080	8 480	8 480
R^2	0.184	0.187	0.359	0.361	0.217	0.220

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the lender's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the lender's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Standard errors are clustered at the lender and borrower and day levels.

Table 2.9:
Participation and Loans-Outstanding Differentials Across Repo and Unsecured Markets, Regressed on Lender Characteristics and TED

	(a) Participation	(b) Participation	(c) Loans	(d) Loans
$\mathbb{1}_s$ * TED	0.005	0.002	0.021	0.003
	(0.01)	(0.01)	(0.03)	(0.05)
$\mathbb{1}_s$ * TED * NPL	−0.002	−0.005	0.008	−0.012
	(0.00)	(0.01)	(0.02)	(0.04)
$\mathbb{1}_s$ * TED * clt	0.024***	0.016	0.122***	0.075
	(0.01)	(0.02)	(0.03)	(0.07)
$\mathbb{1}_s$ * TED * clt * NPL		−0.012		−0.071
		(0.02)		(0.08)
time-invariant interactions		yes		
fixed effects		borrower x lender x day		
N	14 600	14 600	14 600	14 600
R^2	0.503	0.505	0.535	0.537

*p<0.1, **p<0.05, ***p<0.01. The dependent variable in columns (c) and (d) is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. The dependent variable in columns (a) and (b) is *participation*, equal to one if *loans outstanding* is positive and zero otherwise (with coefficients estimated using OLS in a linear probability model). Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the lender's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the lender's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. All valid interactions between $\mathbb{1}_s$, *NPL* and *clt* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.10:
Loans Outstanding Regressed on Borrower Characteristics
and TED, by Collateral Type

	(a) AGS	(b) Unsecured	(c) SGS	(d) Unsecured
TED * NPL	0.031	−0.020	−0.125**	−0.085**
	(0.04)	(0.05)	(0.06)	(0.04)
TED * AGS	0.125**	0.061		
	(0.05)	(0.05)		
TED * NPL * AGS	0.310***	0.131		
	(0.08)	(0.09)		
TED * SGS			0.087***	0.008
			(0.03)	(0.04)
TED * NPL * SGS			0.083	−0.046
			(0.06)	(0.04)
fixed effects	borrower x lender and day			
N	2 660	6 080	1 720	6 080
R^2	0.265	0.195	0.313	0.195

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Column (a) uses only the AGS repo market sample, column (c) uses only the SGS repo market sample, and columns (b) and (d) use only the unsecured market sample. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; *AGS* is the face value of the borrower's AGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one; and *SGS* is the face value of the borrower's SGS holdings measured in the same way as *AGS*. Standard errors are clustered at the lender and borrower and day levels.

Table 2.11:
Loans-Outstanding Differentials Across Collateral Types Regressed on Borrower Characteristics and TED

	(a) Unsecured, AGS $\mathbb{1} \equiv \mathbb{1}(AGS)$	(b) Unsecured, SGS $\mathbb{1} \equiv \mathbb{1}(SGS)$	(c) AGS, SGS $\mathbb{1} \equiv \mathbb{1}(AGS)$	(d) AGS, SGS $\mathbb{1} \equiv \mathbb{1}(SGS)$
$\mathbb{1}$ * TED	0.027	0.091	−0.064	0.116
	(0.04)	(0.07)	(0.06)	(0.07)
$\mathbb{1}$ * TED * NPL	0.085***	0.036	0.165*	−0.115
	(0.03)	(0.03)	(0.08)	(0.08)
$\mathbb{1}$ * TED * AGS	0.009		0.092	
	(0.01)		(0.06)	
$\mathbb{1}$ * TED * NPL * AGS	0.064***		0.272***	
	(0.02)		(0.05)	
$\mathbb{1}$ * TED * SGS		0.024		−0.063
		(0.04)		(0.07)
$\mathbb{1}$ * TED * NPL * SGS		0.044		−0.068
		(0.03)		(0.06)
lower level interactions	yes			
fixed effects	borrower x lender x day			
N	14 960	13 720	6 080	6 080
R^2	0.525	0.542	0.597	0.598

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Each column compares the differential across two of the following three markets: unsecured, AGS repos and SGS repos. The column headings specify the pair of markets being analysed. Each explanatory variable except $\mathbb{1}$ is standardised to mean zero and unit variance. $\mathbb{1}$ is a dummy variable indicating which market (defined in the column headings) the observation corresponds to. The other explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; *AGS* is the face value of the borrower's AGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one; and *SGS* is the face value of the borrower's SGS holdings measured in the same way as *AGS*. All valid interactions between $\mathbb{1}_s$, *NPL*, *AGS* and *SGS* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.12:
Loans Outstanding Regressed on Lender Characteristics
and TED, by Collateral Type

	(a) AGS	(b) Unsecured	(c) SGS	(d) Unsecured
TED * NPL	0.005	0.041	−0.004	0.025
	(0.04)	(0.06)	(0.07)	(0.05)
TED * AGS	0.044	0.022		
	(0.04)	(0.04)		
TED * NPL * AGS	−0.004	0.049		
	(0.04)	(0.04)		
TED * SGS			0.041	−0.018
			(0.15)	(0.10)
TED * NPL * SGS			0.115	0.218**
			(0.13)	(0.10)
fixed effects	borrower x lender and day			
N	2 580	5 620	1 760	5 620
R^2	0.257	0.185	0.298	0.194

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Column (a) uses only the AGS repo market sample, column (c) uses only the SGS repo market sample, and columns (b) and (d) use only the unsecured market sample. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the lender's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; *AGS* is the face value of the lender's AGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one; and *SGS* is the face value of the lender's SGS holdings measured in the same way as *AGS*. Standard errors are clustered at the lender and borrower and day levels.

Table 2.13:
Placebo Regressions of 2006 Loans Outstanding on 2006 Borrower Characteristics and 2008 TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * NPL	–0.045	–0.028	0.155	0.312	–0.021	–0.025
	(0.03)	(0.10)	(0.10)	(0.25)	(0.02)	(0.09)
TED * clt	–0.008	0.013	0.008	0.167	–0.005	–0.010
	(0.07)	(0.12)	(0.10)	(0.22)	(0.02)	(0.09)
TED * NPL * clt		0.034		0.241		–0.008
		(0.20)		(0.31)		(0.15)
N	5 460	5 460	2 680	2 680	8 140	8 140
R^2	0.244	0.244	0.342	0.342	0.209	0.209

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2006 to 5 October 2006. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread from the corresponding date in 2008, lagged one day and measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2005 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2006, measured as the natural logarithm of AUD billions plus one. Standard errors are clustered at the lender and borrower and day levels.

Table 2.14:
Placebo Regressions of 2006 Participation and Loans-Outstanding Differentials Across Repo and Unsecured Markets, on 2006 Borrower Characteristics and 2008 TED

	(a) Participation	(b) Participation	(c) Loans	(d) Loans
$\mathbb{1}_s$ * TED	0.010	0.016*	0.033	0.025
	(0.01)	(0.01)	(0.03)	(0.04)
$\mathbb{1}_s$ * TED * NPL	0.010	0.020	0.046	0.033
	(0.01)	(0.02)	(0.03)	(0.07)
$\mathbb{1}_s$ * TED * clt	0.006	0.018	0.014	−0.001
	(0.01)	(0.02)	(0.07)	(0.09)
$\mathbb{1}_s$ * TED * NPL * clt		0.020		−0.024
		(0.03)		(0.14)
lower level interactions		yes		
fixed effects		borrower x lender x day		
N	17 320	17 320	17 320	17 320
R^2	0.509	0.509	0.522	0.522

*p<0.1, **p<0.05, ***p<0.01. The dependent variable in columns (c) and (d) is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2006 to 5 October 2006. The dependent variable in columns (a) and (b) is *participation*, equal to one if *loans outstanding* is positive and zero otherwise (with coefficients estimated using OLS in a linear probability model). Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread from the corresponding date in 2008, lagged one day and measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2005 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2006, measured as the natural logarithm of AUD billions plus one. All valid interactions between $\mathbb{1}_s$, *NPL* and *clt* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.15:
Robustness to Size: Loans Outstanding Regressed on Borrower Characteristics (Including Size) and TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * size	−0.001	−0.005	−0.044	−0.043	−0.011	−0.011
	(0.05)	(0.05)	(0.07)	(0.08)	(0.04)	(0.04)
TED * clt	0.066	0.056	0.073	0.072	0.077*	0.073*
	(0.04)	(0.05)	(0.06)	(0.06)	(0.04)	(0.04)
TED * size * clt		−0.024		−0.006		−0.014
		(0.04)		(0.08)		(0.03)
fixed effects	borrower x lender and day					
N	5 900	5 900	3 080	3 080	8 980	8 980
R^2	0.189	0.189	0.360	0.360	0.223	0.223

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; *size* is the book value of the borrower's balance sheet at end 2007 or the closest available reporting date, measured as the natural logarithm of AUD trillions plus one; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Standard errors are clustered at the lender and borrower and day levels.

Table 2.16:
Robustness to Size: Participation and Loans-Outstanding Differentials Across Repo and Unsecured Markets, Regressed on Borrower Characteristics (Including Size) and TED

	(a) Participation	(b) Participation	(c) Loans	(d) Loans
$\mathbb{1}_s$ * TED	0.014	0.015	0.060	0.061
	(0.01)	(0.01)	(0.05)	(0.05)
$\mathbb{1}_s$ * TED * size	0.007	0.007	−0.001	−0.001
	(0.01)	(0.01)	(0.03)	(0.03)
$\mathbb{1}_s$ * TED * clt	0.005	0.007	−0.005	0.002
	(0.01)	(0.01)	(0.02)	(0.02)
$\mathbb{1}_s$ * TED * size * clt		0.005		0.022
		(0.01)		(0.02)
lower level interactions		yes		
fixed effects		borrower x lender x day		
N	15 560	15 560	15 560	15 560
R^2	0.501	0.506	0.529	0.534

*p<0.1, **p<0.05, ***p<0.01. The dependent variable in columns (c) and (d) is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. The dependent variable in columns (a) and (b) is *participation*, equal to one if *loans outstanding* is positive and zero otherwise (with coefficients estimated using OLS in a linear probability model). Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; *size* is the book value of the borrower's balance sheet at end 2007 or the closest available reporting date, measured as the natural logarithm of AUD trillions plus one; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. All valid interactions between $\mathbb{1}_s$, *size* and *clt* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.17:
Robustness to Domicile: Loans Outstanding Regressed on Borrower Characteristics (Including Domicile) and TED, by Market

	(a) Unsecured	(b) Unsecured	(c) Secured	(d) Secured	(e) Both	(f) Both
TED * 𝟙(foreign)	0.019	0.022	0.070	0.073	0.038	0.032
	(0.13)	(0.14)	(0.10)	(0.13)	(0.08)	(0.09)
TED * clt	0.071	0.074	0.086	0.089	0.087**	0.081
	(0.05)	(0.08)	(0.06)	(0.07)	(0.04)	(0.06)
TED * 𝟙(foreign) * clt		−0.007		−0.007		0.013
		(0.11)		(0.11)		(0.08)
fixed effects	borrower x lender and day					
N	5 920	5 920	3 080	3 080	9 000	9 000
R^2	0.189	0.189	0.360	0.360	0.223	0.223

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. Columns (a) and (b) use only the unsecured market sample; columns (c) and (d) use only the repo market sample; and columne (e) and (f) combine the unsecured and repo market samples. Explanatory variables are standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: *TED* is the TED spread lagged one day measured in percentage points; 𝟙*(foreign)* is a dummy variable indicating whether the borrower's parent company is located outside of Australia; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Standard errors are clustered at the lender and borrower and day levels.

Table 2.18:
Robustness to Domicile: Participation and Loans-Outstanding Differentials Across Repo and Unsecured Markets, Regressed on Borrower Characteristics (Including Domicile) and TED

	(a) Participation	(b) Participation	(c) Loans	(d) Loans
$\mathbb{1}_s$ * TED	−0.003	−0.003	0.030	0.030
	(0.01)	(0.02)	(0.05)	(0.09)
$\mathbb{1}_s$ * TED * $\mathbb{1}$(foreign)	0.023	0.023	0.041	0.041
	(0.02)	(0.03)	(0.08)	(0.10)
$\mathbb{1}_s$ * TED * clt	0.010*	0.010	0.006	0.005
	(0.01)	(0.01)	(0.03)	(0.05)
$\mathbb{1}_s$ * TED * $\mathbb{1}$(foreign) * clt		0.000		0.001
		(0.02)		(0.06)
lower level interactions		yes		
fixed effects		borrower x lender x day		
N	15 600	15 600	15 600	15 600
R^2	0.502	0.508	0.531	0.537

*p<0.1, **p<0.05, ***p<0.01. The dependent variable in columns (c) and (d) is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. The dependent variable in columns (a) and (b) is *participation*, equal to one if *loans outstanding* is positive and zero otherwise (with coefficients estimated using OLS in a linear probability model). Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. The explanatory variables (pre-standardisation) are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; $\mathbb{1}$*(foreign)* is a dummy variable indicating whether the borrower's parent company is located outside of Australia; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. All valid interactions between $\mathbb{1}_s$, $\mathbb{1}$*(foreign)* and *clt* are included in the regressions but only coefficients on interactions involving *TED* are reported. Standard errors are clustered at the lender and borrower and day levels.

Table 2.19:
Coefficient of Interest from Loans Outstanding Regressions Estimated Across Varying Degrees of Fixed Effects

$\mathbb{1}_s$×TED×NPL×clt	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.016**	0.015*
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Observations	15560	15560	15560	15560	15560	15560	15560	15560	15560	15560	15560	15280
R^2	0.026	0.045	0.046	0.080	0.078	0.159	0.113	0.160	0.505	0.505	0.662	0.703
lower interactions	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
brw FE	no	yes	yes	yes	.	.	.	.	.	.	.	.
day FE	no	no	yes	yes	.	no	.	yes	.	.	.	.
lnd FE	no	no	no	yes	no	.	yes	.	.	.	.	.
sec FE	no	no	no	no	no	no	no	no	no	yes	.	.
brw×day FE	no	no	no	no	yes	no	yes	no	.	.	.	.
brw×lnd FE	no	no	no	no	no	yes	no	yes	.	.	.	.
brw×lnd×day FE	no	no	no	no	no	no	no	no	yes	yes	yes	yes
sec×brw×lnd FE	no	no	no	no	no	no	no	no	no	no	yes	yes
sec×lnd×day FE	no	no	no	no	no	no	no	no	no	no	no	yes

*p<0.1, **p<0.05, ***p<0.01. The dependent variable is *loans outstanding* at the lender-borrower-day-market level, measured as the natural logarithm of AUD millions plus one, from 8 September 2008 to 3 October 2008. The levels of fixed effects vary across columns and are specified in the lower rows. The explanatory variables are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. Only the coefficient on $\mathbb{1}_s$ * *TED* * *NPL* * *clt* is reported. All valid lower-level interactions are also included in the regressions. Standard errors are clustered at the lender and borrower and day levels.

Table 2.20:
Coefficient of Interest from Participation Regressions Estimated Across Varying Degrees of Fixed Effects

$\mathbb{1}_s$×TED×NPL×clt	0.051** (0.02)	0.051*** (0.02)	0.051*** (0.02)	0.051*** (0.02)	0.051*** (0.01)	0.051*** (0.02)	0.051*** (0.01)	0.051*** (0.02)	0.051*** (0.01)	0.051*** (0.01)	0.051** (0.02)	0.049*** (0.01)
Observations	15560	15560	15560	15560	15560	15560	15560	15560	15560	15560	15560	15280
R^2	0.024	0.045	0.045	0.089	0.079	0.192	0.123	0.193	0.533	0.533	0.669	0.706
lower interactions	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
brw FE	no	yes	yes	yes	.	.	.	.	.	.	.	.
day FE	no	no	yes	yes	.	no	.	yes	.	.	.	.
lnd FE	no	no	no	yes	no	.	yes	.	.	.	.	.
sec FE	no	no	no	no	no	no	no	no	no	yes	.	.
brw×day FE	no	no	no	no	yes	no	yes	no	.	.	.	.
brw×lnd FE	no	no	no	no	no	yes	no	yes	.	.	.	.
brw×lnd×day FE	no	no	no	no	no	no	no	no	yes	yes	yes	yes
sec×brw×lnd FE	no	no	no	no	no	no	no	no	no	no	yes	yes
sec×lnd×day FE	no	no	no	no	no	no	no	no	no	no	no	yes

*p<0.1, **p<0.05, ***p<0.01. The binary dependent variable is *participation* at the lender-borrower-day-market level, equal to one if *loans outstanding* is non-zero and zero otherwise, from 8 September 2008 to 3 October 2008. Coefficients are estimated using OLS in a linear probability model. The levels of fixed effects vary across columns and are specified in the lower rows. The explanatory variables are: $\mathbb{1}_s$ is a dummy variable indicating whether the observation corresponds to the repo market; *TED* is the TED spread lagged one day measured in percentage points; *NPL* is the borrower's proportion of non-performing loans to total loans in percentage points, measured at end 2007 or the closest available reporting date; and *clt* is the face value of the borrower's AGS and SGS holdings in the first week of September 2008, measured as the natural logarithm of AUD billions plus one. Each explanatory variable except $\mathbb{1}_s$ is standardised to mean zero and unit variance. Only the coefficient on $\mathbb{1}_s$ * *TED* * *NPL* * *clt* is reported. All valid lower-level interactions are also included in the regressions. Standard errors are clustered at the lender and borrower and day levels.

Chapter 3

IDENTIFYING REPO MARKET MICROSTRUCTURE FROM SECURITIES TRANSACTIONS DATA

3.1 Introduction

Short-term interbank markets are at the core of most developed financial systems. They are the first resort for financial institutions (henceforth loosely termed 'banks') wishing to offset the day-to-day liquidity imbalances that arise from their various business-related cash flows. This pivotal role is the reason central banks use these markets for enacting monetary policy, manipulating the interest rates banks charge each other in order to have flow-on effects to other interest rates throughout the economy. Specifically, the Reserve Bank of Australia (RBA), like many other central banks, targets the rate in the unsecured interbank market for overnight loans, termed the 'cash rate'.

Another key component of short-term interbank markets, besides the unsecured market, is the repo market. Unsecured loans involve movements of cash only, whereas repos, i.e. secured loans, involve simultaneous movement of cash and securities, as borrowers provide and receive back securities as collateral alongside their receipt and repayment of the cash that they borrow.[1] The collateral reduces the risk to the lender – if a repo borrower defaults, the lender takes immediate ownership of the collateral, whereas if an unsecured borrower defaults, the lender

[1] 'Repo' is short for 'repurchase agreement'. A repo is similar to a securities sale paired with a subsequent repurchase.

joins other unsecured creditors with a claim on the borrower's assets. To minimise counterparty risk, RBA uses repos to lend to private banks in open market operations.

Available data on Australian markets indicate that by 2015 the overnight interbank repo market had grown to outsize the overnight interbank unsecured market (Graph 1; the repo data are explained further shortly).[2] Similar patterns have occurred in other regions – between 2006 and 2015, unsecured turnover in the European money market declined from €14 trillion to €3 trillion, whereas secured turnover increased from €21 trillion to €29 trillion (European Central Bank 2015).

Nevertheless, there is little work studying repo-market data at the level of individual loans, compared to a large body of loan-level analysis on unsecured markets. Loan-level data are valuable because, for example, they display the borrower and lender to each position, potentially revealing whether position changes are supply or demand driven, and have a daily or higher frequency, permitting identification of market reactions to shocks. The lack of loan-level analysis is likely due to data availability. Adrian et al. (2014) write "One conclusion emerging from [our work] is the need to better understand the institutional arrangements in [repo and securities lending] markets. To that end, we find that existing data sources are incomplete. More comprehensive data collection would both deepen our understanding of the repo and [securities] lending markets and facilitate monitoring firm-level and systemic risk in these markets."[3] This paper provides an algorithm for extracting loan-level data on over the counter (OTC) repo markets from securities transactions data, to improve the accessibility of loan-level repo data.

Loan-level data on unsecured interbank markets are commonly obtained by applying a similar algorithm, pioneered by Furfine (1999) on US data, that identifies which interbank cash transfers through central-bank payments systems are interbank loans (the 'Furfine algorithm'). The Furfine algorithm identifies pairs of payments that are consistent with a loan principal transferred in one direction, then a principal and feasible interest repayment in the opposite direction the next day. Many subsequent studies have used it to analyse unsecured inter-

[2] This graph focuses on the overnight markets. Section 3.5.1 discusses repo activity at other maturities.

[3] Securities loans are sometimes referred to as special repos, as opposed to general collateral (GC) repos, and are driven by the collateral receiver's demand for the particular collateral received, to, for example, cover a short position in those securities. Since they are often collateralised by cash, they can be difficult to distinguish from GC repos. This paper treats securities loans as a type of repo that is sometimes distinguishable by a lower interest rate.

bank markets at the loan level. Some notable examples are Ashcraft and Duffie (2007), analysing intraday allocation of liquidity in the fed funds market, Afonso et al. (2011), studying daily patterns in US unsecured interbank markets during the global financial crisis, and Acharya and Merrouche (2012), analysing UK unsecured interbank markets during the crisis.

Research on repo markets has tended to rely on datasets that are less detailed or lower frequency. For example, Krishnamurthy et al. (2014) study detailed data at the quarterly frequency, obtained from regulatory filings by a large proportion of US repo counterparties, and Gorton and Metrick (2012a) analyse daily market-wide quotes from US dealers on interest rates and haircuts for various collateral types. Data are more readily available for market segments traded through centralised infrastructure, although these data omit OTC market segments, which can be large, and have tended to be aggregated or anonymised before analysis. Copeland et al. (2014) analyse daily data on collateral held against repos through triparty infrastructure, collected by the Federal Reserve Bank of New York.[4] Mancini et al. (2015) analyse data with several loan-level details but without counterparty information, on repos through the Eurex Repo trading platform in Europe. Fuhrer et al. (2016) is one of the few studies that has analysed loan-level repo data, also sourcing data from the Eurex Repo platform, focussing on the CHF interbank repo market.

This paper describes an algorithm for extracting loan-level repo data on OTC market segments from securities transactions data, and applies the algorithm to conduct a preliminary loan-level analysis of the Australian repo market. Securities transaction data are typically stored by a central securities depository (CSD) that is responsible for maintaining securities ownership records. Via a link to an interbank payments system, most CSDs permit securities transactions to involve simultaneous movement of cash and securities in opposite directions. Accordingly, OTC repos are settled through CSDs alongside other transactions such as secondary market purchases (i.e. outright trades), comparable to how unsecured loans are transacted through centralised payments systems alongside non-loan interbank payments. Analogous to the Furfine algorithm, the objective of the repo-detection algorithm is to separate repo-related transactions from securities transactions occurring for other purposes.

The work is closest to the small literature following Furfine (1999) that assesses and constructs modifications of the Furfine algorithm ('Furfine-type algorithms'). Armantier and Copeland (2012) and Kovner and Skeie (2013) compare data from

[4] Copeland et al. (2012) provide an explanation of triparty repo infrastructure.

the Furfine algorithm with internal data from two banks and with regulatory data, respectively. Kuo et al. (2013) generalise the Furfine algorithm to detect term loans rather than overnight loans. Arciero et al. (2016) calibrate, run and assess the algorithm using European payments data. Rempel (2016) estimates the Furfine algorithm's rates of omissions and false detections, proposing some modifications to improve performance. Brassil et al. (2016) appear the first to detect loans that comprise more than two transactions ('multiple-transaction loans'), finding their augmentation to noticeably improve detections in the Australian unsecured market.

Like Furfine-type algorithms, the algorithm I present (the 'repo-detection algorithm') identifies groups of cash movements that resemble a loan followed by a repayment with interest. However, Furfine-type algorithms rely on the unsecured market convention that loans principals are multiples of, for example, \$100 000, which is not followed in the Australian repo market. Also, securities transactions data contain more information than payments data – the type and quantity of securities transferred. The repo-detection algorithm essentially removes the requirement that loan principals are certain multiples, and includes a requirement that the securities initially provided as collateral are the same type and quantity as those returned. In addition, it detects multiple-transaction repos, like Brassil et al. (2016), although the difference in market conventions across repo and unsecured markets necessitates a dissimilar approach.

The repo-detection algorithm is described in more detail in Section 3.2. First it is represented as a set of formal conditions that map a set of securities transactions into a set of detected repos. Then I describe the procedure for applying these conditions to the data. To detect multiple-transaction repos, I adapt the subset sums problem, a well-known exercise in computer science, to identify groups of transactions whose securities movements, measured by their face value, net to zero.

In Section 3.3 I run the algorithm on securities transactions data from Austraclear that cover several two month windows of securities transactions from 2006 to 2015, and assess its performance. Multiple-transaction repos are common but much lower frequency than two-transaction repos. Using placebo tests that are a special case of those implemented by Rempel (2016), I estimate around 3 per cent of the algorithm detections to be false detections, although excluding multiple-transaction repos reduces this to around 1 per cent. To gauge the incidence of repos missed by the algorithm (but present in the transactions data), i.e. false omissions, I relax some of the conditions assumed in Section 3.2, and find that very few additional repos are detected.

Readers more interested in the Australian repo-market data than the algorithm itself can skip to Sections 3.4 and 3.5. Section 3.4 provides context for the analysis in Section 3.5 by comparing the algorithm data with aggregated repo data from the Australian Prudential Regulation Authority (APRA). The APRA data imply substantially larger repo positions; however, there are reasons to expect differences. In particular, some repo positions reported to APRA are likely transacted through international CSDs (ICSDs) located in Europe with offshore counterparties. Observations in the algorithm data and APRA data have a robust positive relationship with correlations of around 0.5.

Section 3.5 provides a preliminary description of the Australian short-term repo market, i.e. of 14 day maturity or less, as informed by the algorithm data obtained in Section 3.3. In the 2015 window, the average total value of repos open each night is around \$12 billion, compared to around \$5 billion in 2006.[5] The majority of repos are collateralised by Australian Government securities (AGS), although there is little market concentration in particular AGS securities. In 2006 repos with one-week maturity had the largest market share, although by 2015 the market had shifted to largely overnight. Repo rates display substantial cross-sectional variation across an interval of around 50 basis points, and drift upward between 2006 and 2015, consistent with the findings by Becker et al. (2016) and Becker et al. (2017). For maturities up to 14 days, rates are not strongly related to maturity. Larger loans have higher rates and lenders tend to charge lower rates when they borrow more in open market operations.

Section 3.6 concludes. The R code for the algorithm is available upon request.

3.2 The repo-detection algorithm

The algorithm detects groups of securities transactions that appear to comprise a repo, that is, that satisfy a set of characteristics that repos are assumed to have. Transactions not in these groups are assumed to occur for other reasons. The following information about each transaction is required:

- *Settlement time*: the day and time the transaction took place.[6]

[5]Discount securities (i.e. securities without coupon payments such as bank bills) issued by private entities are excluded from the data prior to analysis, so these figures do not include any repos collateralised by them.

[6]With minor modifications, the algorithm would work if only the settlement day is observable, but would not detect some repos that involve more than one transaction on the same day.

- *Counterparties*: account IDs for the securities sender and the securities receiver.
- *Face value (FV)*: the face value of securities transferred.
- *Consideration*: the amount of money, if any, transferred in the opposite direction to the securities.

The key idea is similar to that of the Furfine algorithm, which identifies pairs of payments that are consistent with a loan principal transferred in one direction, then a principal and interest repayment transferred together in the opposite direction the next day. However, Furfine-type algorithms rely on the unsecured market convention that loans are made in round multiples of, for example, \$100 000, which is not followed in the Australian repo market. Moreover, a repo-detection algorithm can utilise a larger set of information, because securities transactions data also contain ISINs and FVs. Relative to Furfine-type algorithms, the difference in market conventions implies the repo-detection algorithm must treat more transactions as potential loan initiations, but the ISIN and FV information reduces the number of subsequent transactions that potentially form a repo with any loan-initiation transaction.

The repo-detection algorithm also detects loans comprising more than two transactions, in contrast to most Furfine-type algorithms, which only search for payment pairs. For example, if the lender increases the loan size before it is repaid, the borrower repays the loan in multiple instalments, there is a collateral top-up or draw-down, or any combination of these occurs, they would be missed by an algorithm detecting only transaction pairs. Brassil et al. (2016) augment the Furfine algorithm to detect unsecured loans comprising more than two payments, finding these loans to frequently occur. In Section 3.3.2 I show that multiple-transaction repos also occur, but are less common than two-transaction repos.

3.2.1 Underlying assumptions

The repo-detection algorithm can be characterised as a collection of conditions that maps a set of securities transactions into a set of 'detected repos'. The conditions have three parameters: *maturity cap*, determining the maximum maturity of detected repos, measured in days as an integer; *interest bounds*, determining the minimum and maximum annualised simple interest rates that detected repos can have, measured as two real numbers; and *transaction cap*, determining the maximum number of transactions that can comprise a detected repo, as an integer.

I express these conditions in plain language and in formal set notation (which readers unfamiliar with the notation can skip). The formally expressed conditions permit a precise definition of a 'detected repo', which is presented after the conditions.

First some notation. Denote a securities transaction x_i as a vector in six-dimensional space, each dimension representing a property of the transaction. Specifically, x_i has elements x_{ij} such that $j \in \{a, b, t, c, s, f\}$, where a and b represent the accounts the securities are sent from and received into (and $x_{ia} \neq x_{ib}$), t represents the settlement time measured in days as a real number (i.e. 0.1 is 2 hours 24 minutes, one tenth of a day), c represents the amount of cash sent from b to a measured in AUD as a real number, s represents the securities' ISIN, and f represents the securities' face value measured in AUD as a real number. Denote by x any set of transactions. Denote $\mathcal{P}$ as the set of 'potentially overlapping detected repos', i.e. the set of detected repos (each repo comprising a set of transactions) before removing repos that include the same transaction as another repo. Denote $\mathcal{D}$ as the set of 'detected repos', i.e. with overlaps removed, so $\mathcal{D} \subseteq \mathcal{P}$.

The conditions on a set of transactions x defined as a 'detected repo' are:

C1. All transactions occur within an interval of days not greater than maturity cap:

Define x_{id} as the integer component of x_{it} so $x_{id} = floor\{x_{it}\}$. Condition C1 states

$$\max\{x_{id}|x_i \in x\} - \min\{x_{id}|x_i \in x\} \leq maturity\ cap.$$

C2. All transactions take place between the same two accounts:

$$|\{x_{ia} \cup x_{ib}|x_i \in x\}| = 2.$$

C3. All transactions involve movement of securities with the same ISIN:

$$|\{x_{is}|x_i \in x\}| = 1.$$

C4. The implied simple interest rate from all cash movements in the set is in the *interest bounds*:

Define the first occurring transaction in x as x_0, so $x_{0t} = \min\{x_{it}|x_i \in x\}$, and the two opposite-direction sets of transactions in x as $x' = \{x_i|x_i \in$

$x, x_{ia} = x_{0a}\}$ *and* $x'' = \{x_i | x_i \in x, x_{ia} = x_{0b}\}$. *Condition C4 states that the scalar solution* r *to*

$$\sum_{x_i \in x'} \frac{x_{ic}}{1 + r(x_{id} - x_{0d})} - \sum_{x_i \in x''} \frac{x_{ic}}{1 + r(x_{id} - x_{0d})} = 0$$

satisfies $365 \times r \in [interest\ bounds]$.

C5. The set involves a net-zero transfer of securities; that is, the FV of securities provided as collateral equals the FV returned:

$$\sum_{x_i \in x'} x_{if} - \sum_{x_i \in x''} x_{if} = 0.$$

C6. At no point the lender returns more securities than it has received:

For all t,

$$\sum_{\{x_i | x_i \in x', x_{it} \geq t\}} x_{if} \leq \sum_{\{x_i | x_i \in x'', x_{it} \leq t\}} x_{if}.$$

C7. The number of transactions in the set is not more than *transaction cap*:

$$|x| \leq transaction\ cap.$$

C8. If there exist overlapping sets satisfying C1 to C7, only sets containing the fewest transactions of those in the overlap are retained:

If $x^1 \in \mathcal{D}$, $x^2 \in \mathcal{P}$ *and* $x^1 \cap x^2 \neq \emptyset$, *then* $x^1 \in \mathcal{D} \Rightarrow |x^1| \leq |x^2|$.

C9. If C8 does not remove all overlapping sets (i.e. overlapping sets have equally few transactions), only one is retained, favouring sets with the shortest implied maturity where possible, or choosing arbitrarily otherwise.[7]

If $x^1 \in \mathcal{D}$ *and* $x^2 \in \mathcal{D}$ *then* $x^1 \cap x^2 = \emptyset$, *and if* $x^1 \in \mathcal{P}$ *and* $x^1 \notin \mathcal{D}$ *then there exists some* $x^2 \in \mathcal{D}$ *such that* $x^1 \cap x^2 \neq \emptyset$.

Definition *If and only if* x *satisfies C1 to C7 then* $x \in \mathcal{P}$.

Definition *A set of detected repos* $\mathcal{D}$ *is any subset of* $\mathcal{P}$ *that satisfies C8 and C9.*

[7] In some cases longer-maturity sets may be selected over others because the cross-checking required would substantially increase computing time. If computing capacity imposed less constraint, the algorithm could be restructured to strictly favour short-maturity sets.

C1 to C5 capture the key assumed characteristics of a short-term repo – opposing transactions between the same accounts within a short period of time, with cash and securities movements consistent with a loan and its collateral. C6 and C7 impose realistic bounds on detected repos that serve to reduce false detections and the required computing capacity.

C8 and C9 handle situations in which a transaction appears in multiple sets that each appear to be a repo. Sets with characteristics that repos tend to satisfy are favoured. Fewer-transaction sets are favoured first, and, in some cases, sets with shorter implied maturities are favoured next. If there still remain overlapping sets, e.g. with equally few transactions and equally short maturities, a set is selected arbitrarily, acknowledging that the remaining sets are close enough to have little impact on the dataset of detected repos.

3.2.2 How the algorithm works and the subset sums problem

To detect two-transaction repos, every possible pair of transactions is checked against conditions C1 to C7, then overlaps are removed by applying C8 and C9 (similar to the original Furfine algorithm). Detecting multiple-transaction repos is less straightforward because for any given transactions dataset, there are far more potential *groups* of transactions than there are pairs. For instance, among a set of 20 transactions, there are 190 possible pairs, but around 15 000 possible groups of five transactions.[8] To detect multiple-transaction repos, I narrow down potential groups using the conditions that can be applied to many groups at once (C1, C2, C3, C6 and C7), then check each remaining group against C5 – i.e. with net zero FV movement. Those that satisfy C5 are then checked for implied interest rates satisfying C4, and overlaps are removed using C8 and C9.

Checking C5 is an application of the subset sums problem – i.e. from a given set of integers, finding all subsets that sum to a particular value. There are many possible approaches, and available computing power is likely to constrain which are feasible. Using the statistical computing language R, I find the matrix algebra approach illustrated in equation 3.1 to be relatively economical. From one particular 'focus transaction' (e.g. with FV equal to 50), a 'candidate vector' is formed of all other transactions that do not necessarily violate conditions C1, C2, C3, C6 and C7. The candidate vector FVs are then signed such that negative indicates se-

[8]From a set of n transactions the number of possible sets of size r is

$$\frac{n!}{r!(n-r)!}.$$

curities movement in the opposite direction to the focus transaction, and positive indicates the same direction (e.g. the vector (25, 30, -80) in equation 3.1). This candidate FV vector is premultipled by a matrix of 0s and 1s that represents every possible combination – which, importantly, R can generate very quickly – and the resulting vector (containing the subset sums) is checked for elements equal to the negative of the focus transaction FV. In equation 3.1, if the focus FV is 50, the second last combination is a feasible combination (i.e. the (0, 1, 1) combination), because its subset sum equals -50.

$$\overbrace{\begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}}^{0/1\ matrix} \overbrace{\begin{pmatrix} 25 \\ 30 \\ -80 \end{pmatrix}}^{candidate\ vector\ FVs} = \overbrace{\begin{pmatrix} 0 \\ 25 \\ 30 \\ 55 \\ -80 \\ -55 \\ -50 \\ -25 \end{pmatrix}}^{subset\ sums} \tag{3.1}$$

The matrix-algebra approach is likely to exceed computing constraints for long candidate vectors (for me the maximum length is 22). In these cases I trim the candidate vector, check the shorter vector using the matrix-algebra approach, and if no repos are detected, apply a slower 'iterative' approach to check the longer candidate vector. Denoting the transaction cap in C7 as K, this approach iterates through $k = 1, ..., K - 1$, checking the FV sums of each possible combination of k candidate-vector elements. This approach may also hit computing constraints (for me the maximum vector length is 45), which is a potential cause of false omissions – i.e. actual repos present in the transactions data that are not detected by the algorithm. Section 3.3.2 shows that this computing constraint very rarely binds.

3.2.3 The algorithm procedure

Before running the algorithm, any transactions involving RBA or ASX are removed. Detected intraday repos are also removed, defined as two transactions on the same day with the same ISIN, FV and consideration, but in opposite directions between two accounts. This assumes an intraday interest rate of zero, consistent with intraday repos on offer from RBA, although other assumptions on intraday interest or fees could be imposed.[9]

[9]There is little evidence in the data that intraday repos occur at other interest rates or with a fixed fee.

For two-transaction repos, the process is essentially:

1. Select a transaction as the 'focus transaction'.
2. Find all other transactions that satisfy C1 to C5 pairwise with the focus transaction (if any). Store the pairs.[10]
3. Repeat steps 1 and 2, treating every transaction in the dataset as a focus transaction. Store all pairs.
4. Sort the stored pairs by increasing maturity, measured in days, with equal maturities ordered arbitrarily.
5. Define the first pair in the sorted list as a detected repo, remove from the list any subsequent pairs that it overlaps, and repeat down to the bottom of the list.

Transactions in detected two-transaction repos are then removed from the dataset and the remaining transactions are checked for multiple-transaction repos. The process is essentially:

1. Select a transaction as the 'focus transaction'.
2. Find all other transactions that satisfy C1 to C3 pairwise with the focus transaction. Store these together in a 'candidate vector' that is linked to the focus transaction.
3. Remove transactions from the candidate vector that would violate C6 in any combination.
4. Repeat steps 1 to 3, treating all transactions as a focus transaction, and collect all candidate vectors.
5. Define a temporary maximum number of transactions, starting with three.
6. Select a candidate vector. Remove any transactions in already-defined detected repos.
7. Select all subsets of the candidate vector without more transactions than the temporary maximum. Keep only those with FVs summing to the focus-transaction FV using the methods discussed in Section 3.2.2, after making negative FVs of transactions in the same direction as the focus transaction. Remove subsets not satisfying C4. If multiple remain, keep only the

[10]In practice, only the locations (e.g. row numbers) of transactions are stored.

minimum-maturity subsets (measured as nights between first and last transaction), and if multiple remain, arbitrarily select one. Define it as a detected repo.[11]

8. Repeat steps 6 and 7, working through every candidate vector.

9. Increase the maximum transaction number specified in step 5 by one, implement steps 6 to 8, and repeat until the transaction cap is reached.

3.3 The algorithm performance

3.3.1 The transactions dataset

ASX provided RBA with securities transactions data from Austraclear, its central securities depository (CSD) for debt securities. Austraclear is the primary CSD for AUD-denominated debt securities, and its records capture every debt-security movement across its users' accounts. Austraclear is linked to the Reserve Bank Information and Transfer System (RITS), Australia's high-value money settlement system, permitting Austraclear account holders to settle securities simultaneously with central bank money. In 2015 Austraclear maintained approximately 2000 accounts held by approximately 850 entities, covering the vast majority of entities active in the Australian financial system.

The dataset comprises eight two-month sample windows, covering September and October for the years 2006 to 2015 excluding 2007 and 2011. All AUD-denominated debt-security transactions in these periods are included except discount securities (i.e. securities that do not have coupon payments) issued by non-government entities. Cash-only transactions are also excluded. Each transaction contains the variables listed in Section 3.2.

3.3.2 Running the algorithm

Throughout the rest of the paper the algorithm is run with the following parameters unless otherwise specified:

- Maturity cap: 14 days.
- Interest bounds: one percentage point around the cash rate range during the two-month data window for that year. For example, in the 2008 window

[11] Alternatively, it would be straightforward to choose from overlapping repos using other characteristics such as implied interest rate or settlement times.

the cash rate moved from 7.25 to 6 per cent, so the interest bounds for the window are 5 and 8.25 per cent. In the 2015 window the cash rate was constant at 2 per cent, so the interest bounds for the window are 1 and 3 per cent. These bounds permit greater volatility in market rates when there is greater volatility in the cash rate.

- Transaction cap: 6 transactions (including the focus transaction).

As mentioned in Section 3.2.3, all transactions involving accounts related to RBA or ASX are removed prior to running the algorithm. In addition, as a preliminary step intraday two-transaction detected repos are removed, based on an assumption that these repos satisfy C2, C3 and C5, and have an implied interest rate of zero.

Table 3.1 reports statistics from running the algorithm on all available data. The computing time for each data window ranges between 2 and 40 minutes. Around 85 to 90 per cent of detected repos have only two transactions (row 2). Almost all of the two-transaction repos are 'unique', meaning that neither transaction in the repo could have potentially been allocated to another two-transaction repo (row 3). Rempel (2016) finds that in the unsecured market, unique detections have lower false detection rates than non-unique detections. Of the multiple-transaction repos, very few were detected using the iterative method, likely reflecting the low proportion of candidate vectors (CVs) longer than 22 (row 6). This part of the algorithm could potentially be removed with relatively little cost, and may substantially speed up computing time. The very low proportion of candidate vectors longer than 45 implies that computing capacity placed very few binding constraints the algorithm.

Table 3.2 reports how many and what type of transactions are in each detected repo. The number of transactions diminishes above three, and the scarcity of repos with six transactions indicates that the transactions cap is relatively inconsequential. Partial repayments are more common than loan increases by a small margin. Collateral movements, i.e. zero-cash transactions within repos, rarely occur, and given the possibility of false detections (discussed in Section 3.3.3), potentially never.[12]

[12] Wakeling and Wilson (2010) report that there is no fixed convention for collateral top ups in Australia. The transactions data are also checked for signs of collateral swaps – i.e. while a repo is open, a provision of a new type of collateral and a return of the original type – and no evidence is found.

3.3.3 Assessing false detections

Define false detections as detected repos that are actually transactions carried out for other purposes, and false omissions as actual repos whose transactions all appear in the transactions data but are missed by the algorithm. In formal notation, if the set of actual repos fully contained in the transactions data is denoted $\mathcal{R}$, then false detections are the set $\{x|x \in \mathcal{D}, x \notin \mathcal{R}\}$ and false omissions are the set $\{x|x \in \mathcal{R}, x \notin \mathcal{D}\}$. If and only if both sets are empty then $\mathcal{D} = \mathcal{R}$.

There is a trade-off between false detections and false omissions; for example, setting wider interest bounds is likely to decrease false omissions while increasing false detections. The choice of parameters and indeed the overall algorithm structure must acknowledge this tradeoff. Notwithstanding, it is straightforward to ex-post modify the algorithm to reduce false detections. For example, Ashcraft and Duffie (2007) only permit unsecured loans to be made at certain times of the day, and Rempel (2016) requires non-unique detected unsecured loans to have interest rates at certain increments. This section will demonstrate that the false detection rate can be substantially reduced by narrowing the interest bounds and bypassing the multiple-transaction repo detection stage.

The most likely cause of false detections is when groups of outright securities trades coincidentally satisfy C1 to C7. For example, a false detection may result when two outright trades occur in opposite directions between the same counterparties, involve the same type and quantity of securities, and have considerations resembling principal and interest payments. Such considerations could be caused by a change in market price that when annualised is within the interest bounds. The required price change is small; for instance, for an overnight repo when the cash rate is 7 per cent, the 'false detection' price change is around 0.02 per cent. In comparison, in the 2012 to 2015 windows the median absolute daily price change for AGS and SGS securities was 0.1 per cent.

False detections can be gauged by performing a placebo test on the algorithm, running it on data or algorithm parameters that are unlikely to capture any actual repos, and counting the detections. For the Canadian unsecured market, Rempel (2016) runs the algorithm on payments data after randomly reshuffling the dates so that consecutive days no longer appear consecutively in the data. Any detected overnight loans must therefore be false detections rather than actual overnight loans. However, the most likely reason for falsely detected repos – groups of outright trades that resemble repos – is dependent on the distance between transaction days. That is, small securities price changes that resemble feasible interest rates are more likely between consecutive days than between days further apart, so changing the ordering would likely underestimate false detections.[13]

Instead, I run the algorithm on the true data with C4 set at 'placebo' interest bounds in which actual repos are very unlikely to occur, but that are roughly equally susceptible to falsely detecting two outright trades. For placebo bounds I use the negative of the 'standard' interest bounds described in Section 3.3.2. Assuming that very small negative and positive securities price movements are equally likely, these placebo bounds and the standard bounds would have a similar number of false detections. This can be interpreted as a special case of the approach by Rempel (2016), one that uses only reshuffles that preserve distance between days, because a detected repo with a negative implied interest rate would appear as a repo with a positive interest rate if the loan and repayment dates were swapped. Since arbitrage relationships lead debt securities prices to move in the opposite direction to the cash rate, I focus on the 2009, 2010 and 2012 windows, in which the cash rate increased 0.25 per cent, stayed constant, and declined 0.25 per cent, respectively. These placebo bounds are the same width as the standard bounds, so are equally susceptible to any other causes of false detections that are randomly uniformly distributed across implied interest rates.

Table 3.3 reports the results from this exercise, including separate statistics for two-transaction and multiple-transaction repos. Overall, the proportion of detections at placebo bounds to detections at standard bounds (the 'false detection rate') is 3.2 per cent.[14] Multiple-transaction repos have a false detection rate of 27.2 per cent, contributing the majority of false detections despite being less than 10 per cent of total detected repos (at the standard bounds). This suggests that a random combination of three or more transactions is much more likely to satisfy C1 to C7 than a random combination of two transactions. For two-transaction repos alone, the overall false detection rate is 1 per cent.

Figure 3.2 visualises the placebo exercise across all of the eight two-month data windows, focussing on detections within 1 percentage point from the cash rate. Consistent with false detections being randomly scattered, they are distributed roughly uniformly across the interest rate intervals, and do not appear less common at implied interest rates further below zero (i.e. towards the left of the chart). In contrast, repo detections peak at around the cash rate and quickly tail off on each side. The false detection rate would therefore be lower if interest bounds were set more narrowly around the cash rate.

[13]The Rempel (2016) approach has the advantage that the distribution of false detections can be estimated by repeating the exercise on many different data reshuffles.

[14]The three years reported in Table 3.3 have higher false detection rates than all other years in the data.

Another way to examine false detections is to look for implied interest rates that are not round numbers. Still, there are several feasible reasons why interest rates on actual repos may not be rounded, so the rate of nonrounded implied interest rates is better considered an extreme upper bound on the rate of false positives. For example: interest rates could be renegotiated during the loan (and the detected repo would show a mean over the life of the repo); repos could be rolled over and interest compounded; interest rates could be agreed as fractions of a percentage point rather than as basis points; or any combination of these.

Table 3.4 reports the number of repos detected with implied simple interest rates that, when measured in basis points with two decimal places, have any non zero decimals ('nonrounded rates'). The probability of a falsely detected random combination of transactions satisfying this criterion is around 1 per cent. Repos spanning policy decisions are excluded because these are more likely to have experienced a renegotiated rate. Overall 14 per cent of detected repos have nonrounded rates. The proportion for multiple transaction repos is 81 per cent. While this is consistent with Table 3.3 showing that multiple transaction repos having the highest false detection rates, the proportion is likely pushed up owing to the fact that repos that involve a transaction between the initial loan and final repayment are also more likely to experience renegotiated, averaged or compounded interest.

3.3.4 Assessing false omissions

False omissions, defined as actual repos that fully appear in the transactions data but are not detected by the algorithm, can only be caused by actual repos violating conditions C1 to C10, or constraints imposed by computing capacity. Computing constraints have been discussed in Section 3.3.2 and likely cause very few false omissions, i.e. substantially less than the proportion of candidate vectors longer than 45, which is close to zero (Table 3.1).

To gauge the likelihood of false omissions caused by condition violations, I count the additional repos that are detected when the conditions are relaxed in ways that accommodate the most likely reasons for their violations. The conditions and the ways I relax them are:

C2. All transactions occur between the same two Austraclear accounts. A feasible violation would be an entity that owns multiple accounts using different accounts for the loan and repayment transactions. To test this, the Austraclear account IDs are replaced with a smaller set of IDs that group accounts held by related parties, before rerunning the algorithm.[15]

C3(i). The loan and repayment transactions involve the same ISIN. Similar in concept to the previous bullet point, ISINs can be replaced with a more general label of AGS, SGS or other.

C3(ii). All transactions involve movement of securities. Cash-only transactions could feasibly occur within repos if the interest is paid in a separate transaction to the principal repayment. Such cases would resemble a repo with zero interest, which can be detected with interest bounds at zero. Notwithstanding, repos with zero interest could also be securities loans.

C3(iii). All transactions involve the same ISIN. In some repo markets collateral for a single repo can be spread across multiple ISINs (e.g. see Fuhrer et al. 2016). Market intelligence has indicated that in the Australian repo market multiple-ISIN repos occur rarely if ever. To test this, I look for four-transaction repos involving two different AGS ISINs, with an implied net-zero FV transfer for each ISIN. Specifically, I count detections that: comprise four transactions; have two lending transactions on one day with different ISINS; and have two repayment transactions on a later day with ISINs and FVs matching the loan transactions.[16]

To minimise the likelihood of any additional detections being false detections, the analysis is restricted to two-transaction repos (or four-transaction repos for C3(iii)). First, two-transaction repos are detected using the standard conditions and removed from the transactions data, then the algorithm is rerun with the relaxed conditions. For some of the condition relaxations, I also report the percentage of additional detections whose implied simple interest rates have two zero decimals when measured in basis points. These detections are much less likely to be false positives.

There appear to be some repos violating C2 and C3, but not many (Table 3.5). There is strong evidence that counterparties to a repo sometimes lend and repay using different accounts, although the frequency is 0.6 per cent of repos detected under the standard conditions. There are also repos with implied interest rates of zero, at 1.6 per cent the frequency of repos detected under the standard conditions. However, most of these involve accounts related to the ICSDs, which are

[15] Only transactions between entities that appear in standard detected repos are retained for this exercise.

[16] Note that these would be detected as two separate repos under the standard conditions if the considerations in the repayment transactions aligned with the two lending transactions plus interest.

more likely to conduct repos related to transactions occurring outside the Austraclear data. Moreover, some of these detections may be securities loans. Overall, the evidence suggests false omissions are negligible.

3.4 Comparing the output with prudential data

RBA also analyses data on repo positions from the Australian Prudential Regulation Authority (APRA). Registered financial corporations with assets above $500 million and Australian-licensed ADIs provide quarterly reports of repo and securities-lending positions held on their domestic books. They report aggregate positions per counterparty type per collateral type, separately for borrowing and lending positions. There are 12 counterparty types, one being RBA, and four collateral types, comprising AGS, SGS, other debt and equities. For example, one of the 96 figures in each entity's quarterly report is lending positions to non-resident counterparties against AGS collateral.

The algorithm data can be made directly comparable by aggregating detected repos that are open at September ends.[17] This results in substantially lower positions than the total quantities reported to APRA (Figure 3.3). There are several likely reasons. For repos against 'other debt', the difference would include any repos against discount securities, which are not in the transactions dataset and therefore not detected by the algorithm. In Australia, secondary markets for private discount securities can have high liquidity, which is a desirable characteristic for repo collateral; for example, Boge and Wilson (2011) report that some bank bills and certificates of deposit are actively traded each morning.

For AGS and SGS collateral, the difference likely relates to repos transacted through infrastructure other than Austraclear. Two international CSDs (ICSDs) – Euroclear and Clearstream – enable their participants to transact AUDdenominated securities that are ultimately held in Austraclear, but without transactions between Austraclear accounts taking place. The securities are held by a nominee with an Austraclear account on behalf of the ICSD, and the ICSD holds them on behalf of its participants. When the ICSD participants transact with each other, the ICSD changes its own records of the securities' ownership, but in Austraclear, the securities remain still in the nominee's account. Since the ICSDs have no direct link to RITS, any AUD cash settled simultaneously with these transactions takes place across accounts at a private bank employed by the ICSD.

[17]For this section I set the maturity cap at 61 days, the interest bounds at 1 percentage point either side of each window?s cash rate range, and the transaction cap at six.

This reason for the difference in data sources – the APRA data capturing repos settled through foreign infrastructure – is consistent with the algorithm figures being closer to the APRA borrowing figures than the APRA lending figures (Figure 3.3). The gap between the APRA borrowing and lending series implies net lending from entities that report to APRA to entities that do not. Becker et al. (2017) attribute a substantial amount of this net lending to demand from non-residents for AUD repo funding as part of international arbitrage positions. Since non-residents are more likely to hold ICSD accounts than Austraclear accounts, it seems likely that these lending positions would not appear in the algorithm data.

There are several other reasons why repos may appear in the APRA data but not in the Austraclear data samples I analyse. Unfortunately it is not possible to precisely account for each difference, which must be kept in mind for the analysis in section 5. Nevertheless, there is widespread ownership of Austraclear accounts across entities active in the Australian financial system (including many related to branches and subsidiaries of foreign banks), and these entities have some incentive to use Austraclear rather than ICSDs owing to Austraclear's ability to simultaneously settle securities against central-bank AUD currency, through RITS. Taking everything into account, it seems reasonable to interpret the algorithm data as the short-term domestic interbank repo market, acknowledging that this omits repos transacted through foreign infrastructure. This corresponds to the typical definition of the Australian unsecured interbank market, which only includes loans that are transacted through RITS.

To more formally compare the datasets, I regress APRA observations on corresponding algorithm observations, similar to the approach by Kovner and Skeie (2013). Three levels of data aggregation are considered: an observation per entity per year per collateral type; an observation per entity per collateral type (i.e. aggregated across years); and an observation per year per collateral type (i.e. aggregated across entities). To better align the datasets, entities whose APRA-data and Austraclear- account IDs cannot be closely matched are removed, the algorithm is run with a maturity cap of 61 days, and the APRA observations exclude positions held with counterparties other than banks, registered financial corporations, other ADIs and non-residents.

Table 3.6 reports the estimates. Regression exogeneity assumptions could feasibly be violated, so the estimates and significance levels should be interpreted with some caution. Notwithstanding, the estimated slope coefficients indicate a statistically significant positive relationship between the algorithm and APRA data in all cases, denoted by the asterisks on the right of the coefficients. The datasets are clearly positively related. Given this, I also test the hypothesis that the two datasets move one-for-one, that is, that the slope coefficient equals one, with significance denoted by the asterisks to the left of the coefficient estimates. In only one case is this hypothesis not rejected. The APRA lending figures tend to vary more than the algorithm figures (i.e. coefficients greater than one), and the APRA borrowing figures tend to vary less (i.e. coefficients less than one). Correlations between the two datasets vary between 0.4 and 0.9, with little discernible difference for the APRA lending and borrowing datasets.

3.5 The Australian Repo Market Microstructure

This section summarises the repo market microstructure inferred from the algorithm data. The data cover the segment of the short-term (i.e. two weeks or less) repo market that is transacted through Austraclear. As discussed in Section 3.4, it seems reasonable to define this segment as the domestic interbank market, excluding from this definition intrabank repos and repos involving banks with little presence in Australia. By comparison, previous RBA analysis of the repo market adopts a broader definition more in line with activity reported to APRA.[18] It is also worth reminding readers that the data in this section cover windows of September and October, which may not be representative of repo activity in other parts of the year, although the APRA data do not indicate much quarter on quarter volatility.

In the following analysis, detected repos with certain characteristics are sometimes excluded to reduce the potential influence of false positives or of repos that are not representative of the information being conveyed. For example, when analysing spreads to the cash rate, repos open across the night after RBA Board meetings are typically excluded, because reference rates used by repo counterparties may diverge from the cash rate in those periods. Also, multiple-transaction repos are excluded where a small number of false positives could skew the information provided.[19]

Because institutions often hold multiple Austraclear accounts, I group accounts into ‘entities’, combining activity by any accounts held under the same parent company. The exception is when the account name indicates it is used on behalf of clients, in which case I label that account, grouped together with any other

[18] Examples include Wakeling and Wilson (2010), Becker et al. (2016) and Becker et al. (2017).

[19] Section 3.3.3 estimates that repos with more than two transactions have a false detection rate of around 27 per cent, whereas repos with two transactions have a rate of around 1 per cent.

client accounts under the same parent company, as being a client entity.[20] Two of the client entities include accounts related to ICSDs. Entities other than client entities and state governments are classified as domestic or foreign, based on the location of their parent company.

3.5.1 Market size, collateral types, interest rates and maturities

Between 2006 and 2015 the market size grew from around \$5 billion to around \$12 billion, measured by the value of outstanding positions on a typical night (Figure 3.4). In 2008 the SGS repo market outsized the AGS repo market. Garvin et al. (2018) show that the repo market expanded substantially during the 2008 window, which contains the period surrounding the Lehman Brothers collapse, and the growth was primarily in SGS repos. In later years the proportion of the market against SGS declined, and in 2015 was less than a tenth the size of the AGS repo market. Throughout the full sample there is relatively little activity in repos against other collateral, although any repos against privately-issued discount securities would not be captured (see Section 3.3).

Table 3.7 reports the ten issuers whose securities are most commonly used as repo collateral, and how many entities use that collateral. Aside from the Australian Government, the most prevalent issuers are the Queensland and NSW state governments, followed by the Victorian and Western Australian state governments. The most used non-AGS and non-SGS collateral is issued by two supranationals and two state-owned German banks. Collateral types tend to be broadly accepted – all are provided by at least 13 different borrowing entities and accepted by at least 12 different lending entities, with higher numbers for the more prevalent types. Collateral issued by private companies is also used – UBS Australia and Westpac are twelfth and thirteenth on the list (not shown in the table) with around 50 repos detected each.

Focussing on the 2015 window, the market does not appear to concentrate in particular ISINs within the AGS category of collateral (Table 3.8). Of the 32 ISINs on issue at some point in the window, all bonds and all but one Treasury note are used as collateral at least once. Each (non-indexed) treasury bond ISIN is used in at least six repos and each treasury indexed bond ISIN is used in at least 16 repos. Treasury bond ISINs are favoured over other AGS ISINs, likely related to the greater quantity on issue. The median treasury bond ISIN is used in 120

[20] Client accounts are identified by the account name containing ‘nominee’, ‘client’, ‘custodian’ or an abbreviation of any of these.

repos, compared to 30 and 3 for the median ISINs for treasury indexed bonds and treasury notes.

Figure 3.5 plots the interest rate spreads to the cash rate for every repo, excluding those open across RBA policy decisions. The position on the x-axis displays the day and time the first transaction in the repo occurred, excluding non-business days. When plotted observations overlap they may not all be visible in the graph; the layering from least visible to most visible reflects their frequency – AGS, SGS, then other collateral.

At each point in time rates tend to be dispersed across around 50 basis points, even within collateral types. The cross-sectional variance overshadows the market-wide variance across days, although the distribution of spreads tightens from 2006 to 2015. This could relate to, for example, a shift towards shorter maturities, discussed later in this section, a change in the dispersion of loan sizes, or changes in the role of the market. Spreads tend to be concentrated at multiples of 5 basis points, indicating common use of the cash rate as a reference rate.

Around 44 per cent of the positive spreads in Figure 3.5 are overnight repos, which indicates that these borrowers did not have unconstrained access to the unsecured market; otherwise they would borrow unsecured at a lower rate and without any collateral obligation. There is also a cluster of repos at 25 basis points below the cash rate, which is the rate lenders with ESAs could earn by, instead of lending in the repo market, simply holding cash overnight in the RBA standing facilities, with no counterparty risk.[21] Their choice to lend could reflect valuation of the repo collateral for reasons other than risk mitigation (e.g. securities loans), or that the lenders do not have direct access to the RBA standing facilities. In later years in the sample, the majority of these lenders are client entities, which are unlikely to have exchange settlement accounts.

Figure 3.6 plots the pattern of increasing spreads evident in Figure 3.5, displaying the median spread each year for AGS and SGS repos. Becker et al. (2016) and Becker et al. (2017) also note increasing market-wide repo rates towards the end of this sample, finding evidence that demand for AUD funds from non-resident borrowers has been contributing to these rises. A noticeable deviation between AGS and SGS spreads occurs in 2008. Garvin et al. (2018) conclude that this is as least partly driven by heightened demand for AGS (i.e. the highest quality collateral) alongside a relative scarcity on issue.

[21] These include repos against all three collateral types, although the repos against AGS and SGS are partly hidden by the other-collateral repos.

For maturities of 14 days or less, there is little evidence of a yield curve (Figure 3.7). Only repos with rounded interest rates are displayed, because these are more likely to have terms negotiated at the start of the repo rather than being rolled over, and therefore the time between the first and last transactions is more likely to represent overall maturity rather than the sum of several rolled over maturities.[22] Spreads for one, two and three day maturities tend to be relatively flat, and spreads at 14 days tend to tick up. Still, overall the patterns are fairly unsystematic.

Figure 3.8 defines maturity as business nights between the first and last transaction, excludes repos most likely to be rollovers, and displays the market share at each maturity. Between 2006 and 2015 the market shifts towards overnight maturities. In all displayed years there is substantial market share at one week maturity (i.e. five business days); however, this declines from around 30 per cent in 2006 to be below 25 per cent in every subsequent year in the sample (including those not displayed). Excluded from Figure 3.8 is a borrower-lender pair that in 2015 contributes a disproportionate share of turnover; including them makes the overnight market share above 50 per cent.

For an indication of whether repos occur at maturities above two weeks, the algorithm can be run with a 61 day maturity cap. For these longer maturity repos, turnover is a more useful measure of activity than share of outstanding positions.[23] In 2006, 11 per cent of total turnover detected is at 30 days (retaining non-business days), but in 2015, aside from a small spike of around 0.5 per cent of turnover at 21 days, activity at maturities longer than 14 days is scarce.[24]

Next I analyse repo interest rates by regressing them on other repo characteristics. Treating each detected repo from 2012 to 2015 as an observation, I regress interest rates on appropriate transformations (specified in Table 3.9) of the following variables: the quantity of lender's OMO borrowing that day;[25] the size of

[22]Rounded interest rates have two zero decimals when measured in basis points and rounded to two decimal places. See Section 3.3.3 for further discussion.

[23]To measure share of outstanding positions for longer-maturity repos, adjustments need to be made to account for longer repos experiencing greater truncation at the ends of the two-month data windows. However, these adjustments can amplify the sensitivity of the output to false detections, so analysing turnover is more transparent.

[24]These turnover figures are underestimates of the true values due to the truncation issue discussed in the previous footnote. Still, the degree of underestimation depends primarily on the repo?s maturity, so spikes in turnover share relative to shares at similar maturities are somewhat reliable indicators of greater activity.

[25]OMO borrowing is measured as funds received on that day from the Austraclear account that RBA uses for OMO, also obtained from the Austraclear transactions data.

the repo (i.e. cash lent); a dummy indicating whether the lender subsequently sold the securities received as collateral while the repo was still open, indicative of the repo being used to cover a short sale;[26] dummies for maturity buckets; dummies for collateral types; and a dummy indicating whether the collateral was a reference bond in the futures market.[27]

Index individual repos by i, such that the space of i includes dimensions for lender l, borrower b and day d (and therefore also year y), and label the set of explanatory variables X. I estimate two equations:

$$rate_i = \alpha_d + X\beta + \varepsilon_i \tag{3.2}$$

and

$$rate_i = \alpha_d + \alpha_{lb} + X\beta + \varepsilon_i \tag{3.3}$$

Equation 3.2 includes day fixed effects to control for any day-to-day fluctuations in market-wide rates. Equation 3.3 includes day fixed effects and borrower*lender*year fixed effects, focussing on variance in rates within borrower-lender pairs. This ensures estimates reflect heterogeneity in the explanatory variables after holding lenders and borrowers constant, rather than heterogeneity across borrowers and lenders.

Table 3.9 reports the coefficient estimates. The following bullets provide some discussion.

- *Lender's OMO*: Equation one indicates a positive relationship; however, this is driven by cross-sectional variation – entities that (on average) borrow more in OMO also being those that charge higher rates to repo borrowers.[28] The equation two estimates show that when entities have higher OMO borrowing, they charge their regular borrowers lower rates than usual. The effect is statistically significant but not large. If entity A borrows nothing in OMO on day one and \$1.2 billion on day two – an unusually large but not infeasible amount – it will lend at around 2 basis points less on day two. The negative relationship is consistent with OMO participants sometimes borrowing more than necessary and lending out spare liquidity at a marginally lower rate.

[26]For this variable, Austraclear transactions with nonzero considerations that are not part of repos are interpreted as outright trades.

[27]For each regression reported in this paper, repos that occur through separate transactions but are otherwise virtually identical – i.e. same counterparties, settlement days, collateral type and interest rate – are aggregated into one repo, to prevent estimates overweighting these repos. For the other analysis in this paper, aggregation of these repos would be less consequential.

[28]Further unreported estimations support this interpretation.

- *Consideration*: Loan size has a highly significant and positive relationship across both specifications. When a loan doubles in size, the rate increases by around a third to half a basis point. Possible explanations could include a thinner market for larger loans that tilts market power towards the lender, or compensation to the lender for a higher concentration of counterparty risk in that borrower.

- *Short sale*: Repos covering short sales (likely to be securities loans) have rates around 2 basis points lower than others. The sign is as expected, with cash lenders compensating borrowers for receiving the collateral. The dummy is a proxy and may result in underestimates if it also picks up repos used for other purposes.

- *Maturities*: After controlling for counterparty heterogeneity, maturities do not have a significant effect, consistent with Figure 3.7, but the ordering of coefficients is consistent with a small term premium.

- *Collateral type*: SGS repos tend to have a rate 1 basis point higher than AGS repos. Bartolini et al. (2011) find a similar but wider disparity in the US – in data up to 2006, rates on repos against Treasury securities are around 5 basis points lower than rates on repos against agency securities. Other-collateral repos tend to have a rate around 7 basis points lower than AGS repos. These repos potentially comprise more securities loans.

- *Futures collateral*: These repos have significantly higher rates by around one basis point. This is consistent with the arbitrage position discussed in Wakeling and Wilson (2010) and Becker et al. (2016) whereby banks short futures and buy the underlying bonds to capitalise on a negative spread between the futures and underlying prices. Banks can fund the bond purchase by borrowing repo using the bond as collateral, putting upward pressure on rates for these repos.

3.5.2 Market structure in 2015

The proportion of turnover, measured as the sum of the cash side of all repos in the window regardless of maturity, is highly skewed towards a single lender-borrower pair, contributing around half of the total (Figure 3.9). Aside from this pair, the bulk of turnover is distributed across 15 to 20 entities, most of which both lend and borrow. Five of the six most active of these entities are Australian, and most of the remaining activity is by foreign and client entities.

Figure 3.10 illustrates the market as a network after excluding repos with state government entities. Each node is an entity, coloured by domicile. The shape represents its average net overnight position across all counterparties – circles are net lenders, squares are net borrowers, and the size of the shape represents the value of their net overnight position (using a nonlinear scale). Each (undirected) edge represents a bilateral position, with the thickness representing the total gross value of lending and borrowing between that pair (also using a nonlinear scale).

There is a distinct core-periphery split.[29] Around a third of entities are 'periphery' entities that are not linked with each other and each have only one or two counterparties. Around two thirds are 'core' entities, each with five or more counterparties in the core, plus counterparties in the periphery. The core is well integrated; most have more than 10 counterparties. On the other hand, if data in this sample are representative of the current market structure, periphery entities are somewhat segmented and their market access might easily be disrupted if there are problems with their one or two core counterparties. The market structure seems inconsistent with core entities' primary activity being intermediation for the periphery, given core entities' relatively large net positions. Among the core, the pattern is more consistent with a market 'churn' related to entities seeking other entities with which to offset day-to-day liquidity surpluses and deficits.

Repo rates tend to vary across counterparty types. Figure 3.11 plots the estimated difference in rates across lender and borrower types, with 95 per cent confidence intervals, relative to average rates on repos between Australian lenders and Australian borrowers. Specifically, the coefficients are from a re-estimation of equation one on 2015 data with X comprising: eight domicile dummy variables representing the nine types of lender-borrower domicile combinations, using loans from Australian lenders to Australian borrowers as the baseline; dummies for 2-7 and 8-14 day maturity buckets; and dummies for collateral types. Rates are highest for repos from Australian lenders to client borrowers, in line with the Becker et al. (2017) explanation that non-residents' demand for funding has put upward pressure on repo rates in recent years. Overall, rates charged by Australian lenders tend to be higher than rates charged by other lenders. The lowest rates are from client lenders to foreign borrowers.

There is little evidence of collateral rehypothecation in the full set of algorithm data. Specifically, there are no detected repos in which the borrower provided securities that it had received as collateral in another repo earlier in the same day (identifying securities by their ISIN).

[29] Brassil and Nodari (2018) discuss core-periphery structures in more detail with reference to the Australian unsecured interbank market.

3.5.3 Haircuts

A repo haircut (sometimes called an initial margin) is defined as the proportion by which the collateral value exceeds the cash lent:

$$haircut = \frac{market\ price \times face\ value}{consideration} - 1 \tag{3.4}$$

Haircuts are intended to keep the lender fully collateralised should the market price of the securities move adversely. Typically they are higher for securities with more volatile prices, which have potential to fall further in price while the repo is open. For current RBA lending in OMO, the lowest haircut is 1 per cent, corresponding to AGS and SGS, and the highest haircut is 20 per cent, corresponding to asset backed securities.

To obtain implied haircuts from the algorithm repo data, the repo dates and collateral ISINs need to be aligned with market prices for the securities. I do this using the (mid) closing prices each day for all AGS and SGS repos in the 2012 to 2015 windows from RBA and Yieldbroker. For multiple transaction repos, the implied haircut is measured using only the first transaction.

Implied haircuts tends to be scattered around zero (Graph 3.12). In 2014 and 2015 there are clusters around 1 and 2 per cent which reflect only a small subset of entities. Implied haircuts are often negative, in contrast with repos involving RBA. These negative haircuts are spread across various counterparties, ISINs and settlement times, and, gauging by the incidence of rounded interest rates (discussed in Section 3.3.3), do not contain a noticeably larger proportion of false positives.

There are several possible reasons why negative haircuts are observed. For example, these repos may comprise a high proportion of securities loans – in which negative haircuts would be expected because the securities provider rather than the securities receiver requests the collateral buffer – or repo counterparties may use different pricing data to that used here, such as intraday prices or prices generated by internal models.

To further investigate implied haircut patterns I regress equations 3.2 and 3.3 from Section 3.5.1, replacing $rate_i$ with $haircut_i$ and limiting the sample to AGS and SGS repos between 2012 and 2015. I use the same explanatory variables X, but also include the repo rate in basis points, and a dummy variable for whether the repo was open over a cash rate decision. If haircuts represent value to the lender and a cost to the borrower, we may expect a negative relationship with repo rates, if counterparties negotiate by raising one and lowering the other. To lenders, higher haircuts reduce counterparty risk and temporarily increase liquid-assets holdings. To borrowers, haircuts may represent the cost of capital for securities financing, being the gap between funds obtained by borrowing against the security and funds required to purchase the security (Ashcraft et al. 2011).

Table 3.10 reports the estimates. The cash-rate decision dummy is significant and positive across both equations, estimating that these repos have haircuts 0.17 percentage points higher than other repos. This may reflect repo counterparties reacting to expected securities price volatility, as AGS and SGS prices tend to move when the cash rate moves. The dummy for SGS repos is significant and positive in equation two, consistent with SGS having lower market liquidity than AGS. Aside from these, haircuts show few statistically significant or large relationships with other explanatory variables. There is little relationship between haircuts and repo rates, indicating they are not simultaneously negotiated. The coefficient on the 'short sale' dummy is also not significant, which is at odds with the notion that the negative haircuts correspond to securities loans.

3.5.4 Intraday timing patterns in 2015

Graph 3.13 illustrates variance in repo volumes, values, rates and maturities within an average day in the 2015 window. Some relatively low-value repos tend to occur in the early morning. A drop in volume and value occurs around 4.30pm. Brassil et al. (2016) show that unsecured lending peaks during the 'close' session between 4.30pm and 5.15pm, when banks receive information on how the processing of SWIFT customer payments has affected their liquidity position. Given their findings, Graph 11 indicates a substitution from the repo to the unsecured market at this time, and the pickup in repo values between 4.30pm and 5.30pm may reflect entities turning to the repo market to find funds not sources in the unsecured market.

Average spreads rise throughout the day, although the pattern is not robust to controlling for other variables such as lender and borrower characteristics. The pickup in spreads after 6pm is driven by a small number of repos and potentially not representative of the overall market. Average maturities decline gradually from 4.5 days around 9am to 1 day after 6pm. Consistent with the discussion in the previous paragraph, this could be indicative of early market activity being driven by predictable funding needs, and late activity comprising more short-term funding resulting from unexpected liquidity imbalances.

3.6 Conclusion

This paper provides an algorithm for extracting loan-level repo data from securities transactions data, to capture OTC repo-market segments, and uses the algorithm for a preliminary loan-level analysis of the Australian repo market. Related algorithms are commonly used for loan-level analysis of unsecured interbank markets around the world. Yet, until now, there has been little access to loan-level data on repo markets.

The algorithm detects groups of securities transactions that occur between the same two counterparties within a 14 day interval. The cash legs of the transactions must be consistent with loans and repayments at a feasible interest rate. The securities legs of the transactions must involve the same type and quantity of securities provided and then returned. Assessment of the algorithm output indicates that around 97 per cent of the detected loans are actual repos, and that the requirements imposed on repo transactions by the algorithm are very close to the behaviour that actual repos follow. The algorithm data capture a smaller market than reported in prudential data, likely in part reflecting repos with offshore entities that are reported to the prudential regulator but do not appear in the transactions data. Correlations between the two datasets are around 0.5.

I also provide the first analysis of the Australian repo market microstructure, covering several two-month samples between 2006 and 2015. Over these years the market size grew, the distribution of interest rates drifted up and tightened, and there was a shift towards shorter maturities. Interest rates tend to depend on loan size and the types of counterparties, but not maturity. Turnover is skewed towards a highly active pair, and the market network structure is split between a tightly integrated core and a segmented periphery that each deal with only one or two counterparties. Repo haircuts do not display obvious patterns, appearing randomly distributed around zero.

Figure 3.1: Size of Overnight Repo and Unsecured Markets

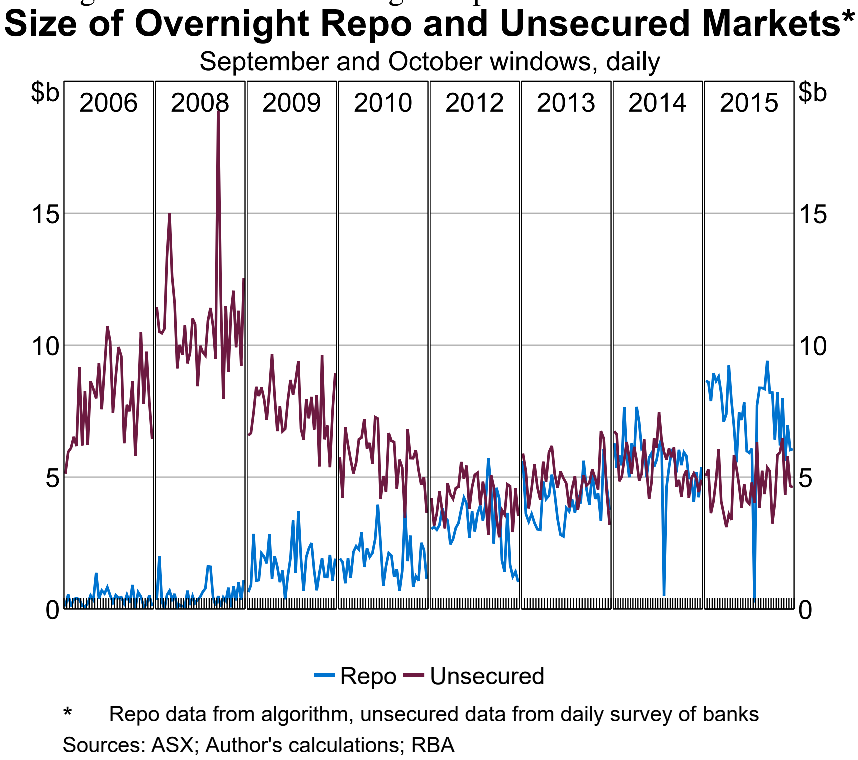


Figure 3.2: Repo Detections at Placebo Rates

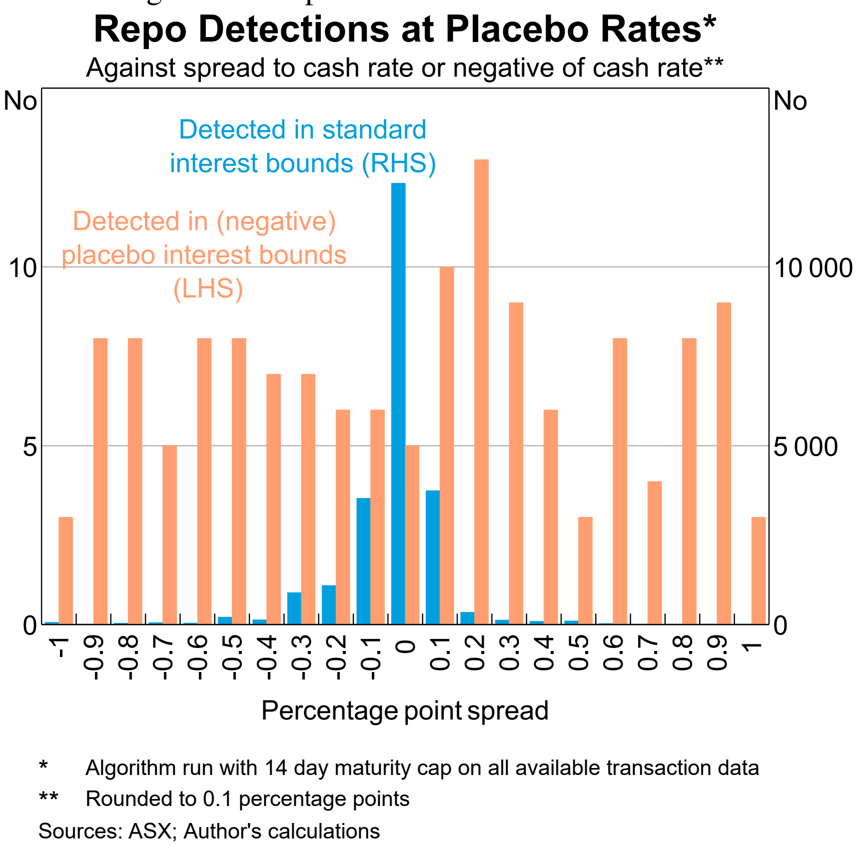


Figure 3.3: Outstanding Repos (excl RBA) by Data Source

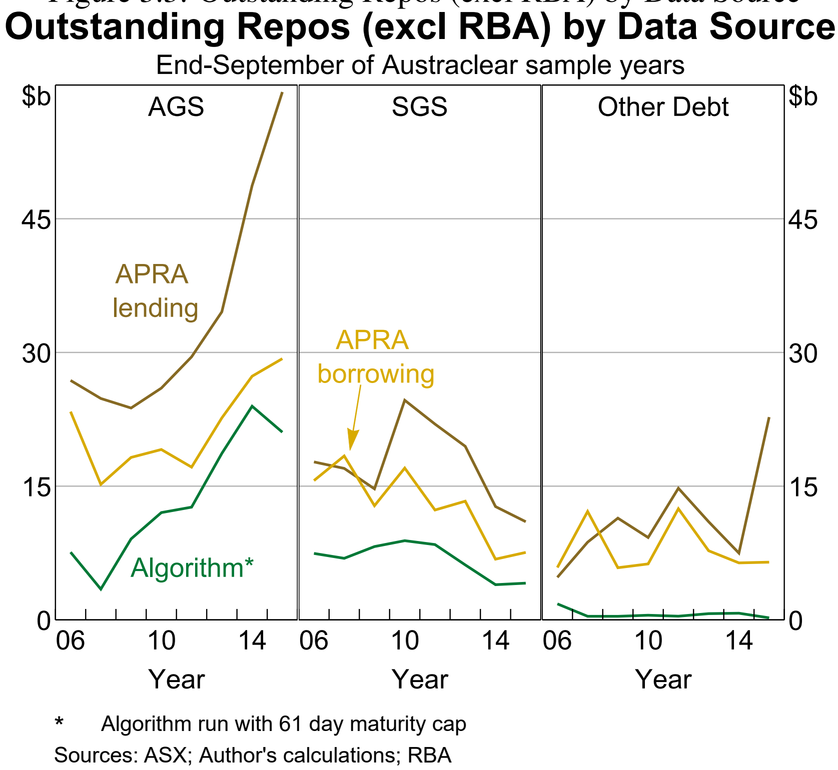


Figure 3.4: Outstanding Repo Positions

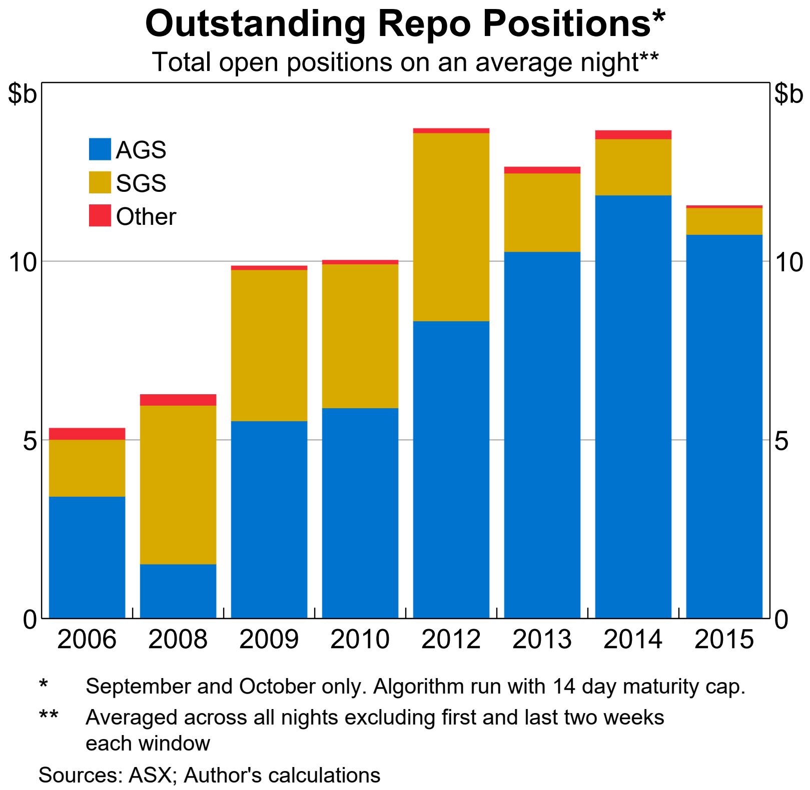
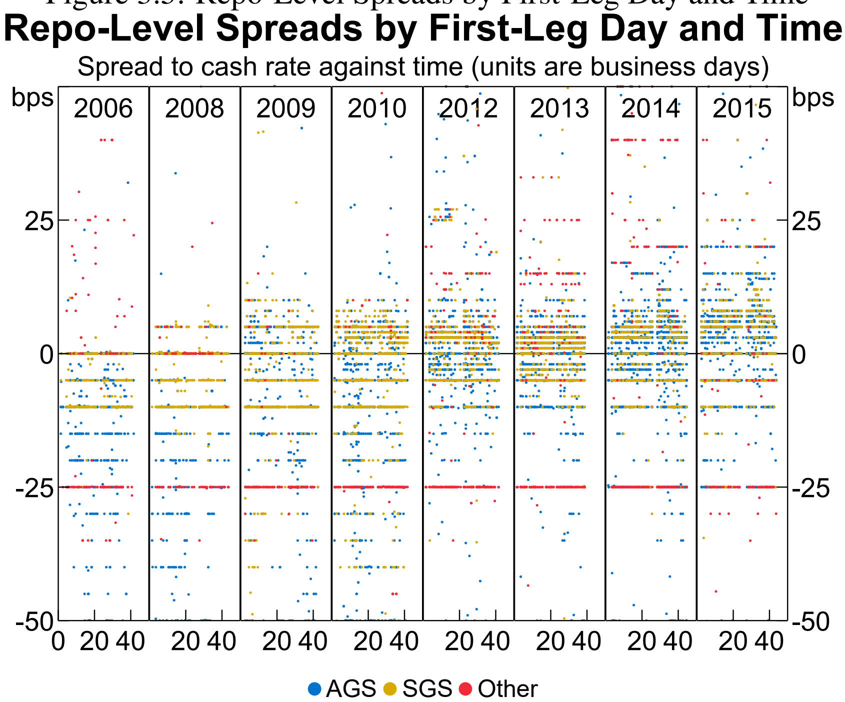


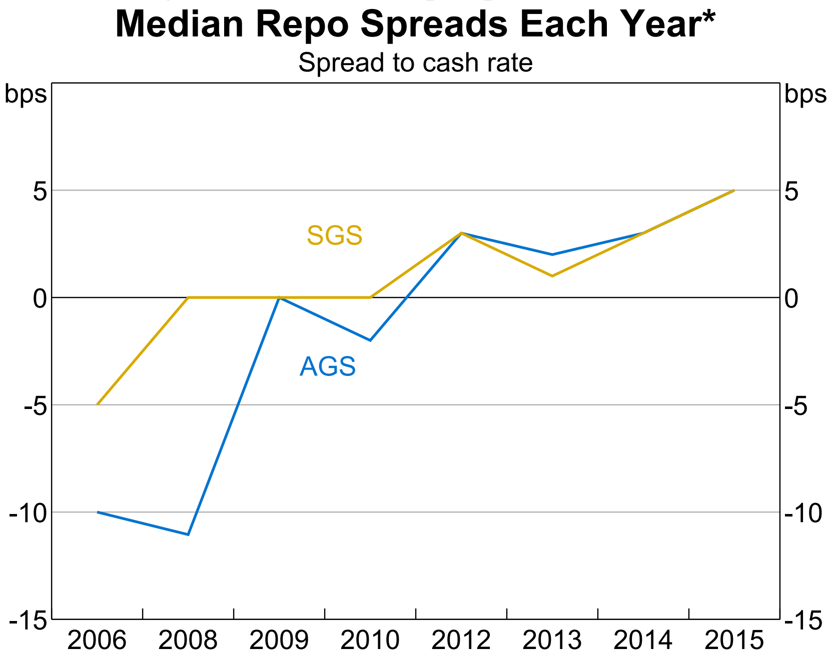
Figure 3.5: Repo-Level Spreads by First-Leg Day and Time



* September and October only. Algorithm run with 14 day maturity cap. Repos spanning policy decisions excluded.

Sources: ASX; Author's calculations; RBA

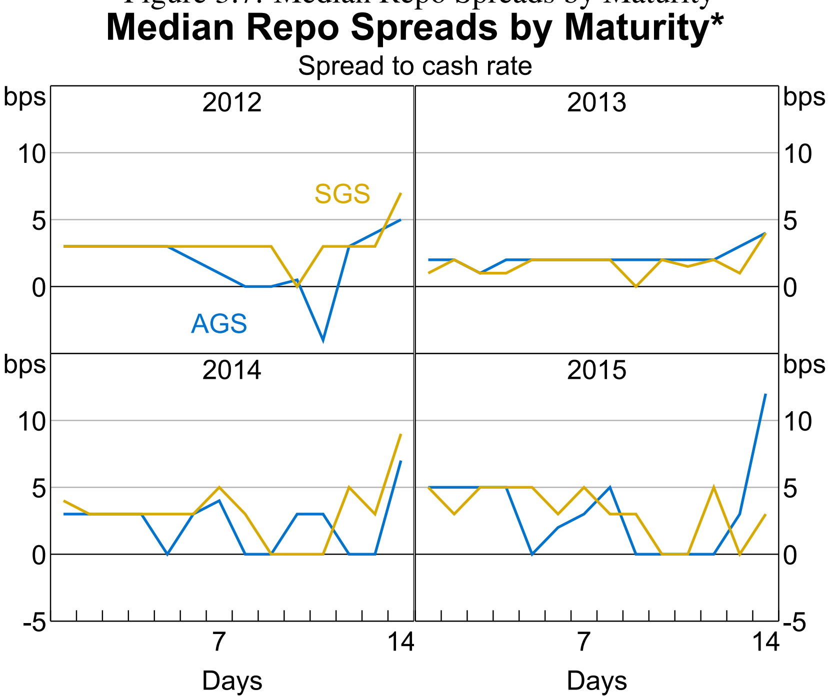
Figure 3.6: Median Repo Spreads Each Year



* September and October only. Algorithm run with 14 day maturity cap. Repos spanning policy decisions and one high turnover lender-borrower pair excluded.

Sources: ASX; Author's calculations; RBA

Figure 3.7: Median Repo Spreads by Maturity



* September and October only. Algorithm run with 14 day maturity cap. Repos with more than two transactions, spanning policy decisions or with nonrounded interest rates excluded. One high turnover borrower-lender pair excluded.

Sources: ASX; Author's calculations; RBA

Figure 3.8: Repo Maturities by Share of Value

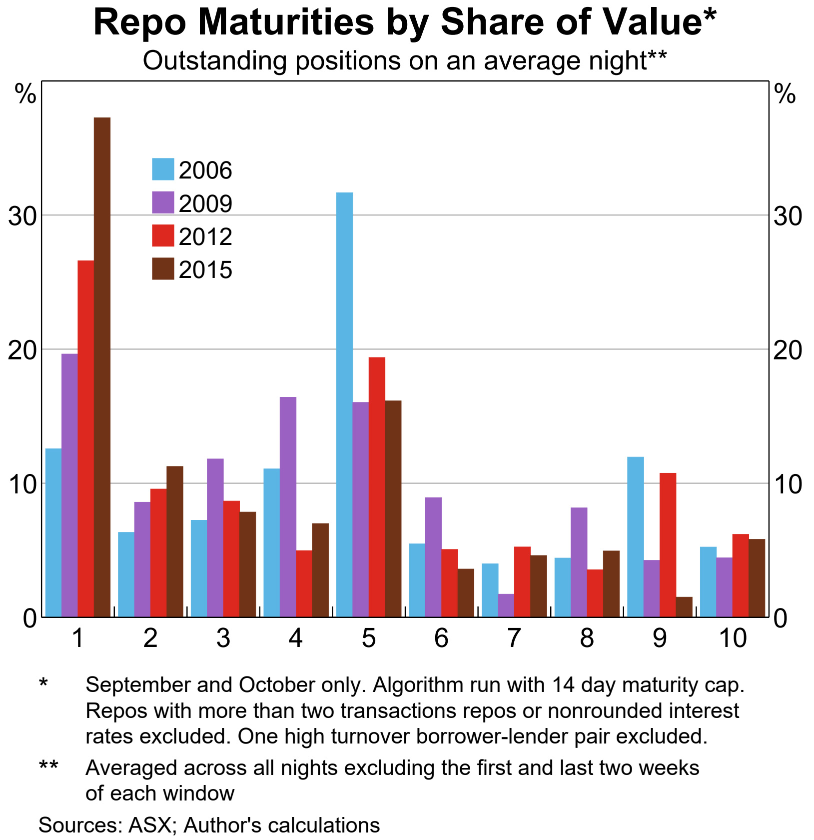
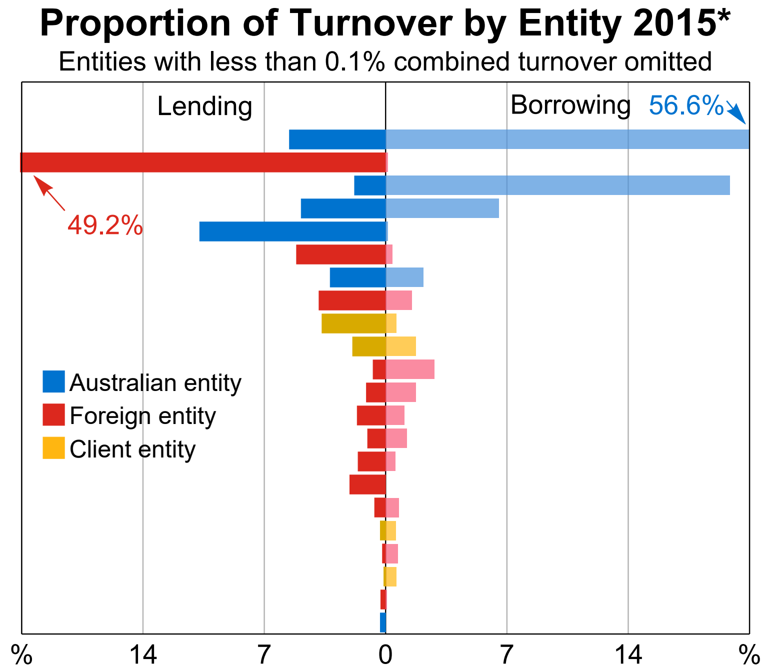


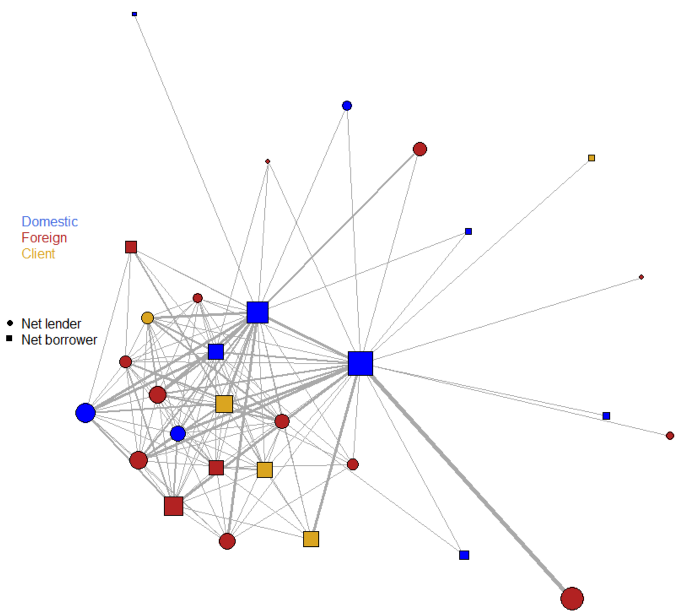
Figure 3.9: Proportion of Turnover by Entity 2015



* Algorithm run with 14 day maturity cap. Entities ordered by combined borrowing and lending turnover. Excludes repos with state government entities.

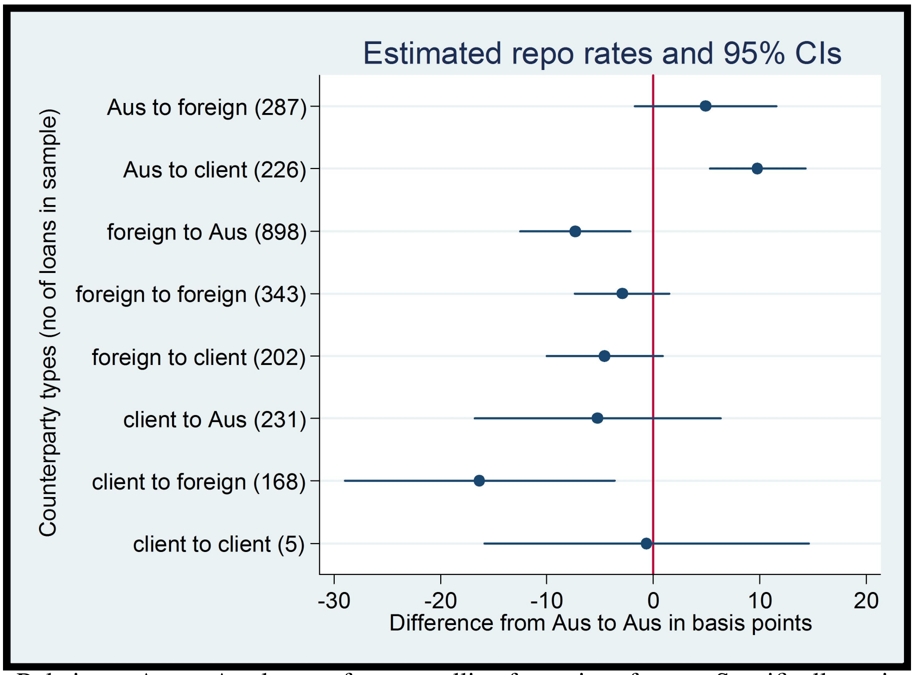
Sources: ASX; Author's calculations

Figure 3.10:
Network of Repo Positions 2015



Average daily positions within sample window. Node size represents average overnight position netted across all counteparties (using a nonlinear scale). Edge size represents average gross position between that counterparty pair (also using a nonlinear scale).

Figure 3.11:
Repo Spreads by Lender and Borrower Types 2015



Relative to Aus to Aus loans, after controlling for various factors. Specifically, estimates are from a regression of equation 3.2 (with day fixed effects) using explanatory variables: dummy variables for the counterparty-combination types; dummies for 2-7 and 8-14 day maturity buckets; and dummies for SGS and private collateral. Standard errors are clustered at the lender level.

Figure 3.12: Repo-Level Haircuts by First-Leg Day and Time

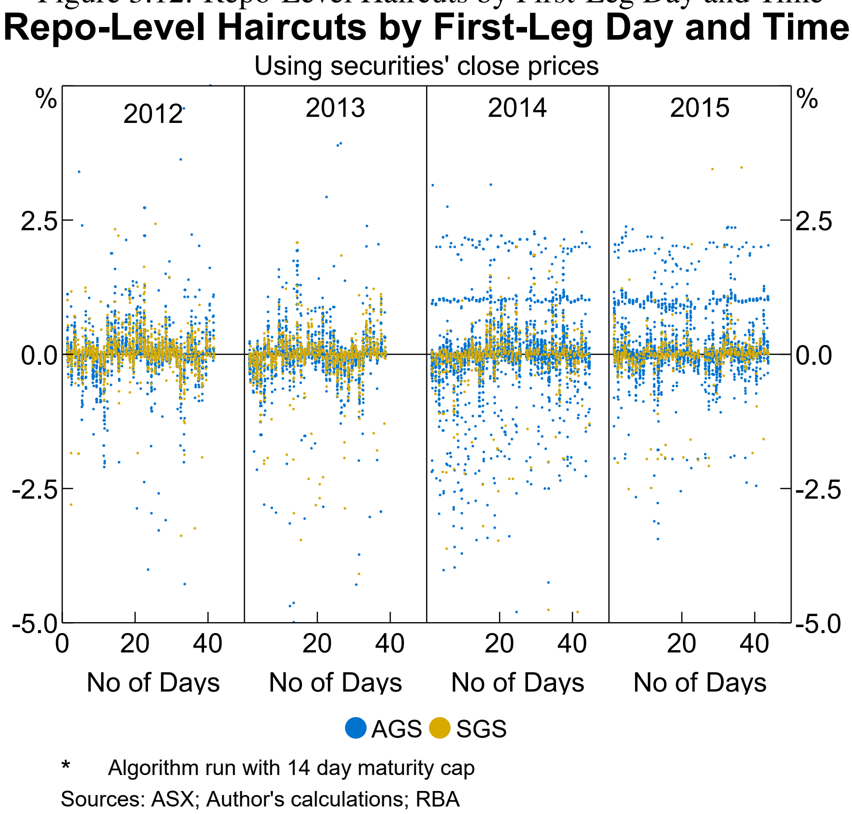
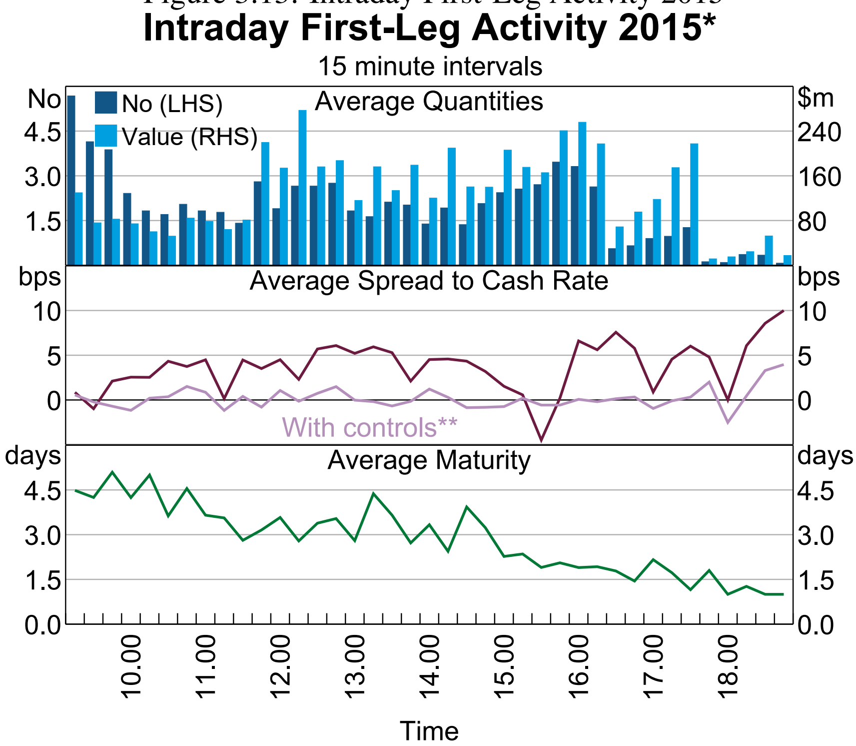


Figure 3.13: Intraday First-Leg Activity 2015



* September and October only. Algorithm run with 14 day maturity cap. Repos with more than two transactions or spanning policy decisions excluded. One high turnover borrower-lender pair excluded.

** Average of residuals from regressing spreads on maturity and dummies for day, security type (AGS, SGS and other) and lender-borrower pairs

Source: RBA

Table 3.1:
Statistics on Repo-Detection Procedure

	2006	2008	2009	2010	2012	2013	2014	2015
Total repos (excl intraday)	1282	1459	2177	3273	4075	3856	4702	3891
Two transactions	1160	1324	1993	2959	3773	3620	4420	3659
Unique	1132	1313	1966	2917	3676	3478	4190	3478
More than two transactions	122	135	184	314	302	236	282	232
Iterative method	0	0	1	15	27	0	8	0
CVs with length ≤ 22 (%)	99.3	84.9	94.5	92.3	96.7	98.9	90.7	99.1
CVs with length ≤ 45 (%)	100	92.5	99.5	99.6	99.8	100	97.7	100
Longest CV	28	89	50	54	54	30	83	36
Intraday repos	50	51	81	80	140	423	223	176
Total transactions[(a)]	20 699	19 942	27 625	32 829	38 323	36 248	42 045	37 105
Proportion in repos (%)	13.6	16	17.2	21.9	23.1	24.5	24.4	22.7

(a) Excluding transactions involving RBA or ASX and transactions with zero consideration (which appear to mostly be for account-maintenance purposes).

Table 3.2:
Structures of Detected Multiple-Transaction Repos

	2006	2008	2009	2010	2012	2013	2014	2015
Three transactions	104	107	137	206	203	179	202	182
Four transactions	16	20	35	70	66	45	49	35
Five transactions	1	6	8	20	26	5	19	11
Six transactions	1	2	4	18	7	7	12	4
Partial repayment	77	98	112	215	185	149	179	136
Loan increase	54	56	97	162	160	121	152	126
Collateral movement	0	0	2	0	1	0	1	0

Table 3.3:
Estimating False Detections using Placebo Interest Bounds

	2009	2010	2012	Total
Total (%)	1.56	3.75	3.54	3.16
Two transaction repos (%)	1	1.32	0.82	1.03
Multiple transaction repos (%)	7.78	28.04	38.31	27.24

As percentage of detections at standard interest bounds.

Table 3.4:
Detected Repos with Nonrounded Simple Interest Rates

	2006	2008	2009	2010	2012	2013	2014	2015	Total
Total (%)	14.35	14.61	14.34	15.52	13.17	12.56	10.81	9.29	14.35
Two trns repos (%)	7.6	7.91	7.45	8.51	7.33	7.64	6.27	5.12	7.6
Multiple trns repos (%)	81.19	89.52	91.88	92.7	93.85	94.76	88.41	82.81	81.19

As percentage of detected repos. Nonrounded is defined as any nonzero decimals when measured in basis points with two decimal places. Repos spanning policy decisions are excluded from calculations.

Table 3.5:
Detected Repos with Nonrounded Simple Interest Rates

	2006	2008	2009	2010	2012	2013	2014	2015	Total
C2: Generalised account-ID detections									
Account reduction ratio	51:85	51:81	52:85	53:83	48:80	47:74	46:71	46:72	na
Detected	29	8	11	39	15	11	9	6	128
With rounded rates (%)[a]	84.21	71.43	70	97.3	92.31	80	71.43	66.67	85.32
Relative to standard (%)	2.5	0.6	0.55	1.32	0.4	0.3	0.2	0.16	0.56
C3(i): Generalised security-type detections									
Detected	14	7	5	20	17	22	33	29	147
With rounded rates (%)[a]	0	0	0	0	0	0	0	0	0
Relative to standard (%)	1.21	0.53	0.25	0.68	0.45	0.61	0.75	0.79	0.64
AGS or SGS	1	4	3	10	6	12	4	4	44
C3(ii): Zero implied-interest detections									
Detected	17	9	17	30	96	83	32	38	322
Relative to standard (%)	1.47	0.68	0.85	1.01	2.54	2.29	0.72	1.04	1.41
Detected excluding ICSDs	0	2	1	11	20	11	12	12	69
C3(iii): Two ISIN, four transaction detections									
Detected	0	0	0	0	0	0	0	0	0

(a) Detected repos spanning policy decisions removed from this proportion calculation.

Table 3.6:
OLS Regressions of APRA Data on Algorithm Data

	Entity and year level		Entity level		Year level	
	Lending	Borrowing	Lending	Borrowing	Lending	Borrowing
Intercept	0.533***	0.44***	1.383**	1.619***	5.174***	3.779***
	-0.067	-0.049	-0.549	-0.34	-0.887	-0.697
Slope	***1.452***	***0.518***	***2.485***	**0.757***	***2.057***	0.983***
	-0.163	-0.067	-0.323	-0.107	-0.218	-0.129
R squared	0.21	0.17	0.47	0.43	0.8	0.73
Correlation	0.45	0.41	0.69	0.65	0.9	0.85
Sample size	309	304	69	69	24	24

***p<0.01; **p<0.05. Asterisks on the left of slope coefficients test whether coefficients equal one.OLS standard errors in parentheses. Variables measured in $ billions.

Table 3.7:
Ten Most Common Collateral Types (by Issuer) Across Full Sample

Issuer	Detected repos	Borrowers	Lenders
Australian Government	15875	33	34
Queensland Treasury Corporation	2895	27	30
New South Wales Treasury Corporation	2278	30	29
Treasury Corporation of Victoria	859	27	24
Western Australian Treasury Corporation	849	30	23
European Investment Bank	309	23	17
KFW Banking Group (Germany)	271	21	19
South Australian Financing Authority	170	19	20
Landwirtschaftliche Rentenbank (Germany)	119	18	12
International Bank for Reconstruction and Development	79	13	12

Algorithm run with 14 day maturity cap.

Table 3.8:
Each AGS ISIN's Frequency of Use as Collateral in 2015

	Treasury bonds	Treasury indexed bonds	Treasury notes
Number of ISINs on issue	22	7	3
Lowest frequency of an ISIN	6	16	0
Median ISIN frequency	120.5	30	3
Highest frequency of an ISIN	213	37	4

Frequency refers to number of repos detected. Algorithm run with 14 day maturity cap. Repos with more than two transactions excluded.

Table 3.9:
Interest Rates (bps) Regressed on Loan Characteristics 2012-2015

	(a)	(b)
Lender?s OMO (IHS $b)[(a)]	6.365*	-1.590**
	(3.65)	(0.6)
Consideration (log $m)	1.124***	1.517***
	(0.33)	(0.13)
Short sale (D)	-2.085	-1.899***
	(1.95)	(0.44)
Maturity 2-7 days (D)	2.600**	0.633
	(1.1)	(0.41)
Maturity 8-14 days (D)	3.919***	0.606
	(1.24)	(0.76)
SGS (D)	1.313*	1.307***
	(0.69)	(0.37)
Other collateral (D)	-5.66	-6.880*
	(5.61)	(3.88)
Collateral referenced in futures (D)	0.792*	0.892**
	(0.46)	(0.32)
Fixed effects	day	day & borrower*lender*year
N	12218	12047
R squared	0.095	0.489

*p<0.1, **p<0.05, ***p<0.01; standard errors clustered at the lender level with 26 clusters; state govt entities removed from regressions.

Table 3.10:
Haircuts (pps) Regressed on Loan Characteristics 2012-2015

	(a)	(b)
Repo rate (bps)	0.075	0.056
	-0.42	-0.1
Consideration (log $m)	0.054	0.005
	-0.04	0
Short sale (D)	-0.014	-0.007
	-0.03	-0.01
Lender's OMO (IHS $b)	0.01	0.008
	-0.05	-0.03
Maturity 2-7 days (D)	-0.018	0.026*
	-0.05	-0.01
Maturity 8-14 days (D)	-0.03	-0.015
	-0.04	-0.02
Cash rate decision (D)	0.172***	0.167***
	-0.04	-0.03
SGS (D)	-0.026	0.032**
	-0.02	-0.01
Futures security (D)	-0.019	0.018
	-0.03	-0.05
Fixed effects	day	day & borrower*lender*year
N	11240	11061
R squared	0.170	0.594

*p<0.1, **p<0.05, ***p<0.01; standard errors clustered at the lender level with 26 clusters; state govt entities removed from regressions.

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