The Liquidity Premium under a Floor System of Monetary Policy

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Abstract

Can a government exhaust the liquidity premium on its debt by borrowing too much? I show that under a scarce-reserve system, the causal impact of government debt is confounded by the endogenous dynamics of the supply of reserves (set by the central bank), which is a close substitute. I use data from New Zealand to analyze the liquidity premium under a floor system, where the interest on reserves and their supply are disentangled. I find a negative causal impact of government debt and the interest rate of monetary policy. A simple model explains these results.

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1 Introduction

Investors pay a premium for the liquidity service flows provided by government debt (beyond what would be predicted by standard asset pricing in the presence of liquidity risk) and this makes public debt a near-money asset that carries a convenience yield. Do liquidity premiums on government bonds depend on the supply of debt? Can a government exhaust the premium by borrowing too much? The recent buildup of public debt in advanced economies to fight the Covid pandemic poses these new questions for the convenience yield literature. Well known empirical evidence for the U.S. suggests the answer is no: the liquidity premium is determined by the monetary policy rate, regardless of how much the government borrows (Nagel, 2016). I show that isolating the role of the debt supply is challenging because the central bank endogenously alters the supply of reserves (a close substitute in the provision of liquidity services) and this has not been addressed in previous results. This paper argues that the way New Zealand conducted monetary policy allows me to circumvent this endogeneity present in other data sets (including U.S. data). In particular, in July 2006, the Reserve Bank of New Zealand (RBNZ) transitioned to a floor system, where the central bank does not need to adjust the quantity of reserves to hit its monetary policy rate target. My results show that debt supply has a negative causal impact on the liquidity premium and that the interest on reserves, stripped of its linkage to reserves supply, also reduces the liquidity premium.

The potential exhaustion of convenience yields has significant fiscal and monetary policy implications. Convenience yields are at the center of current fiscal capacity analysis. The safety and liquidity premia expand the budget constraint of the government, allowing the government debt-to-GDP ratio to be above the discounted present value of primary surpluses (Mian et al., 2021; Reis, 2021; Jiang et al., 2022). Moreover, liquidity premia lower short-term equilibrium interest rates (Lenel et al., 2019) and are at the center of unconventional monetary policy transmission in Krishnamurthy and Vissing-Jorgensen (2011) and Del Negro et al. (2017).

In the first part of the paper, I show that central bank reserves and the supply of T-bills have a strong positive correlation (crowding-in) when central banks conduct monetary policy under a corridor system (or scarce-reserve system). The United States and other advanced economies implemented such a system until 2008. The central bank targets an interbank rate and supplies the amount of reserves that achieve that target through open market operations. If there is an increase in demand for liquidity by banks, the central bank prevents the interbank rate from increasing by supplying extra reserves. The same would happen if the government issued more T-bills (which also provide liquidity to banks). This positive correlation suggests that reserves and T-bills respond endogenously to the same shocks along the business cycle. If reserves and T-bills are close substitutes, then the supply of reserves is a confounding factor for identifying the causal impact of Treasury supply on the liquidity premium.

To isolate the causal impact of the supply of government debt on the liquidity premium, one needs to look at instances where the central bank hits its monetary policy rate target without altering the supply of reserves. Monetary policy implemented through a floor system offers such an opportunity. The central bank supplies abundant reserves to the point where the demand for liquidity by banks no longer responds to the quantity of reserves (banks' demand for reserves becomes flat as in Poole's (1968) model). In this scenario, the monetary policy rate used by the central bank to hit its target is the interest it pays on these reserves (the IOR). The supply of reserves ceases to be endogenous to the stance of monetary policy and along with the IOR they are now two independent tools. Therefore, a regression analysis of the liquidity premium on the supply of T-bills uncovers the causal impact of the debt supply. Including the IOR in the regression uncovers the effect of the monetary policy rate that works not through the quantity of reserves.

I implement this exercise empirically. Although the U.S. Federal Reserve has conducted something close to a floor system since late 2008 (when it increased the reserve supply and started paying interest on them), the U.S. data is unsuitable for this purpose. This is because the Quantitative Easing (QE) programs deployed in 2009-2014 endogenously altered the supply of reserves and the IOR remained unchanged until December 2015. For this reason, I use data for New Zealand, whose central bank transitioned to a floor system in 2006 but did not reach the zero lower bound nor deployed QE until March 2020. The regression analysis shows that the supply of T-bills is a significant determinant of the liquidity premium and that the effect of the IOR is negative.

A simple monetary model can explain these results. Households derive utility from consumption and holding liquid assets, either deposits or T-bills. Banks are in their flat portion of their reserves demand, and the central bank implements a floor system as described above. The model proposes two mechanisms through which an increase of the interest on reserves reduces the liquidity premium on government debt. First, it reduces the price level, which increases the real value of existing liquid assets, and this increased real supply reduces the marginal value of liquidity. Second, the rise in the interest on reserves reduces the cost of liquidity for households, as the higher rate passes onto the yield on deposits. This effect reduces their willingness to pay for the liquidity of T-bills, resulting in a drop in their liquidity premium. Notice, however, that the total yield of T-bills also increases, so the government ends up paying higher yields on its debt and enjoying a lower premium. This point towards interference of monetary policy absent under a scarce-reserves system. The model is calibrated for New Zealand's data, but its implications are potentially crucial for the U.S. The FOMC's January 2019 statement says that the Committee intends to keep an abundant reserves framework going forward, where the IOR is the primary tool for its monetary policy goals and "in which active management of the supply of reserves is not required".

This paper contributes to the empirical literature on convenience yields by clarifying the role of the supply of government debt and monetary policy. While early papers found a negative impact of debt supply on convenience yields (Krishnamurthy and Vissing-Jorgensen, 2012; and Greenwood et al., 2015), Nagel (2016) was the first to notice the connection between the liquidity of T-bills and monetary policy, as the central bank sets the price of the most liquid asset in the economy (money). He notes that the liquidity premium of T-bills in the United States correlates positively with the monetary policy rate. He adds the federal funds rate to the right-hand side of the regression and finds that the coefficient on the supply of debt loses all its significance. His interpretation relies heavily on the perfect substitutability of reserves and T-bills in the provision of liquidity services. If the government suddenly supplies fewer T-bills, the central bank can step in by lowering the federal funds rate and supplying more reserves. Therefore, the central bank, by elastically supplying new reserves, can fully control the price of both assets. Building on this mechanism, Vandeweyer (2021) finds that T-bills supply becomes statistically significant in regressions using U.S. data after 2008. Based on this fact, he develops a model that explains why deposits and T-bills would no longer be perfect substitutes.

I show that the positive correlation between reserves and T-bills does not support the crowding-out between reserves and T-bills at the center of these papers' mechanism. On the empirical side, I contribute to clarifying the causal role of debt supply by choosing a setup where the supply of reserves is plausibly exogenous. In addition, in New Zealand's data the interest on reserves shows more variation than in the U.S. after 2008, which is the data used in Vandeweyer (2021). On the theoretical side, my model matches the positive correlation between T-bills and reserves, and extends Nagel's (2016) model to explain the liquidity premium under an abundant-reserves system. The model also complements Vandeweyer's (2021) by showing that under an abundant-reserve system, the supply of T-bills negatively affects the liquidity premium regardless of the degree of substitutability between debt and deposits.

I also contribute to the recent literature that uses convenience yields to estimate the fiscal capacity of the government. The negative causal impact of government debt I estimate complements the analyses in Mian et al. (2021) and Reis (2021), whose models assume that larger outstanding debt reduces the revenue earned from issuing "convenience" assets. I also provide new insights on the role of monetary policy, which highlights the need for further research.

I choose to rely on a monetary model as it better highlights the role of liquidity premia for both deposits and government bonds. Monetary policy under abundant reserves has been studied in other types of models (see Curdia and Woodford, 2011; Cochrane, 2014; Canzoneri et al., 2017; Afonso et al., 2020; Piazzesi et al., 2021; Benigno & Benigno, 2021). Their focus, however, is not on the determination of the liquidity premium of government debt and the interactions between the fiscal and the monetary authority.

The paper proceeds as follows. Section 2 shows the main empirical exercises, while Section 3 presents the model and runs counterfactual exercises highlighting monetary and fiscal policy interactions. Section 4 concludes. The Online Appendix provides more detailed data and model descriptions.

2 Empirical analysis

I follow the literature's convention and measure the liquidity premium of T-bills by taking their spread against other assets of similar maturity and credit risk. The intuition is that, since the maturity and credit risk are the same, the remaining spread must be due only to their liquidity services. The spread, then, is a measure of the extra price investors are willing to pay for the liquidity of the T-bills. For New Zealand data, I use two assets that are comparable to T-bills: 3-month bank bills and 6-month term deposits.

Bank bills are a common investment in Australia and New Zealand: it is a promise by the borrower to pay the the face value at maturity. It is considered a safe investment because they are "accepted" (guaranteed) by a bank. In accepting the bank bill, the bank makes the payment at maturity, regardless of the repayment ability of the borrower. Investors can buy bank bills from a bank, for an agreed face value, an agreed term, and a quoted rate of interest. The bank bills are then endorsed by the bank to acknowledge the change in ownership. Upon maturity, the bank will pay the full face value, which includes the initial purchase price and the interest receivable. An additional feature of investing in bank bills is that should you require funds before the due date, the bank will purchase the bank bill at the prevailing interest rate. Although this last feature might make them as liquid as a T-bill, they have consistently traded at yields above T-bills, with the spread spiking during the turmoil of 2008.

The spread between term deposits rates and T-bill rates are one of the measures used in Krishnamurthy and Vissing-Jorgensen (2012) for U.S. data. Term deposits in New Zealand, similar to the U.S., are a safe investment where investor lock-in a competitive interest rate for a fixed term. Investors are usually not allowed to redeem their money before the term's expiration. Some banks allow it in specific circumstances and require early notifications to do so. Therefore, the spread should account for the liquidity provided by the T-bill.

The liquidity premium measured with these two assets is sizeable. The bank bill has a yield 28 basis points above T-bills on average for January 1996-July 2021. The term deposit has a larger spread, of 63 basis points on average. The larger spread for the term deposit might come from two sources. First, its maturity is six months rather than three. Second, this might be due to the higher liquidity of the bank bill, which makes it more similar to the T-bill. Recall that the bank bill can be sold at any time during the term of the instrument, while the investment in the term deposit is locked in for the whole term. Standard deviations are high for both measures: 24 and 80 basis points, respectively.

2.1 Empirical model

Next, I explain my empirical strategy to isolate the causal impact of Treasury supply on the liquidity premium. A good starting point is to consider the following regression:

$$LP_t = \beta_0 + \beta_1 FFR_t + \beta_2 (Tbills/GDP)_t + \epsilon_t \tag{1}$$

where LP_t is the liquidity premium of T-bills, FFR_t is the level of the monetary policy rate set by the central bank (the federal funds rate in the case of the United States) and $(Tbills/GDP)_t$ is the total supply of T-bills. Nagel (2016) estimates this regression for the United States with data from 1991 to 2011, when the U.S. Fed was mostly using a corridor system of monetary policy (until late 2008). His results show that $\hat{\beta}_1 > 0$ and $\hat{\beta}_2 = 0$. This leads Nagel (2016) to conclude that the supply of T-bills does not affect their liquidity premium, which would only depend on monetary policy decisions by the central bank. The explanation would go as follows: under scarce reserves, the level of the FFR is linked ono-to-one with the supply of reserves, which in turn determines the cost of issuing deposits by banks. Deposits and T-bills must be very close substitutes in the provision of liquidity services and therefore the central bank, by elastically supplying new reserves, can fully control the price of both assets. For example, if the government were to suddenly supply less T-bills, the central bank can step-in by supplying more reserves, and private banks increase their supply of deposits. This implies a central bank that is continually offsetting new issuances of T-bills by an opposite change in the supply of deposits. At the end, the central bank defines the liquidity premium on all liquid assets (deposits and closer substitutes like T-bills), and the composition between the two is irrelevant.

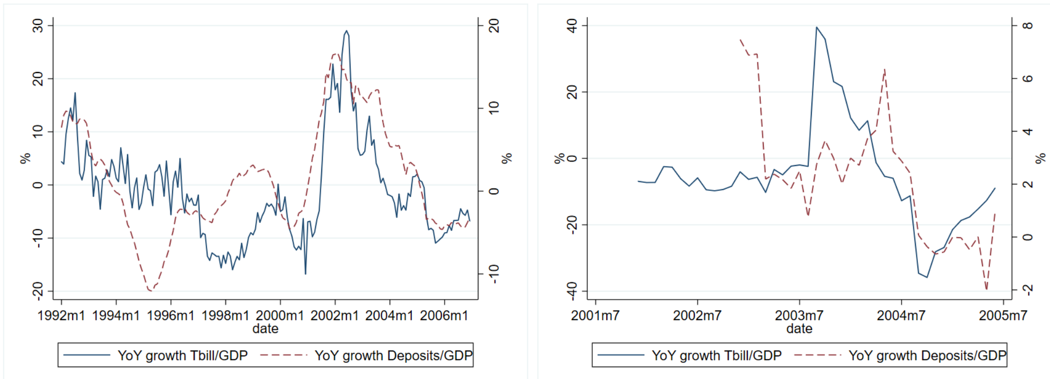
However, data for periods when central banks implemented a corridor system shows that T-bills and deposits do not crowd-out each other, but rather they are crowded-in. In Figure 1a I show the correlation between T-bills supply and deposits supply for the United States between 1992 and 2006. The correlation between the yearly growth rates of T-bills and Deposits is 0.62, significant at the 1% level. For New Zealand the sample is shorter, but a positive correlation still emerges (0.44, significant at the 1.4% level, for December 2001 to June 2005, before the floor system). This result is robust to using reserves-to-GDP instead of deposits.

The crowding-in is also consistent with the result in Krishnamurthy and Vissing-Jorgensen (2015), who estimate the extent to which Treasury debt crowds out short-term liabilities by the financial sector. They find an economically significant crowding out, but it works through Treasury supply crowding out non-checkable short-term debt (savings deposits) rather than liquid deposits like checking accounts.

Figure 1 suggests that both the supply of deposits and the supply of T-bills are endogenous and respond similarly to the business cycle. The positive correlation between supply of deposits and T-bills implies that the former is a confounding factor when estimating the causal impact of the supply of T-bills on the liquidity premium. Therefore, to isolate the causal impact of T-bills

Figure 1: Correlation between T-bills and deposits (scarce-reserve system)

(a) United States: Jan. 1992 - Dec. 2006 (b) New Zealand: Dec. 2001 - Jun. 2005



on their liquidity premium, one needs to look at instances where the central bank does not alter the supply of reserves to achieve its target.

Based on this evidence, assume the following decomposition for the federal funds rate:

$$FFR_t = \gamma_1 i_t^m + \gamma_2 M_t^s + \gamma_3 (Tbill/GDP)_t \tag{2}$$

where M_t^s is the supply of reserves and i_t^m is the interest paid on reserves (IOR) by the central bank. The federal funds rate is the rate at which banks borrow reserves from other banks. Under a scarce-reserve system, banks are willing to pay a premium for the liquidity of reserves. As they operate in the downward-sloping portion of their demand for liquidity, a larger supply of reserves lowers the willingness to pay for them, and so $\gamma_2 < 0$. As T-bills can also provide liquidity, they will have a similar effect, and therefore γ_3 will also be negative. In practice, since the Fed sets a target for the federal funds rate, whenever the government issues more T-bills, the central bank needs to issue more reserves to prevent money market rates from going over the target.

The true model for the liquidity premium would then be:

$$LP_t = \beta_0 + \beta_1 \gamma_1 i_t^m + \beta_1 \gamma_2 M_t^s + (\beta_1 \gamma_3 + \beta_2)(Tbill/GDP)_t + \epsilon_t \tag{3}$$

Equation (3) shows that the effect of the supply of debt can be decomposed into a direct effect (for which Nagel (2016) estimates $\hat{\beta}_2 = 0$), and an effect working through their substitutability with reserves ($\beta_1 \gamma_3$, and we know $\hat{\beta}_1 > 0$).

I claim that a floor system offers the opportunity to analyze the liquidity premium at instances where the central bank does not need to alter the supply of reserves to achieve its target. Under a floor system, the central bank issues abundant reserves, beyond the point where reserve demand by banks becomes flat (and does not respond to supply). This can be understood through the model of banks' reserve demand in Poole (1968) or Afonso et al. (2020). In these models, banks demand reserves only to meet reserve requirements, and there are no frictions in the interbank market. At high levels of aggregate reserves, demand is flat, with banks indifferent among a wide range of reserve holdings as long as market rates (including the interbank rate) equal the interest rate paid on reserves. Since in this case central banks operate on the flat part of the demand for reserves, they in practice have two independent instruments: the policy rate (the IOR) and the supply of reserves. The former is used to meet its mandate on inflation, and the latter can be used for some other goal. Importantly, the supply of reserves is no longer endogenous to the conduct of monetary policy and clears up this confounding factor of the impact of debt supply.

As monetary policy implemented through a floor system does not work through the supply of reserves, I assume that $\gamma_2 = 0$ in (3). Therefore, I estimate the following regression:

$$LP_t = \alpha_0 + \alpha_1 i_t^m + \alpha_2 (Tbill/GDP)_t + \epsilon_t \tag{4}$$

In this equation, coefficients will have a different interpretation as in (1). α_1 captures the effect of the level of interest rates stripped from its effect through the supply of reserves. A monetary policy tightening no longer involves a decrease in the supply of reserves. The expected sign of $\widehat{\alpha}_1$ is negative as it sets the return on the alternative liquid asset. The coefficient $\widehat{\alpha}_2$ will capture the causal effect of the supply of T-bills, no longer confounded by the response of the supply of reserves.

The U.S. Fed has managed something very close to a floor system since October 2008 when it expanded the supply of reserves and started paying interest on them. However, for most of the time since then, this policy has coincided with the conduct of QE (where reserve supply is endogenous) and didn't alter the IOR for seven years. For that reason, I study the liquidity premium under a floor system with data from New Zealand. In July 2006, the Reserve Bank of New Zealand (RBNZ) began the transition from a symmetric channel system to a floor system (see the Appendix for a detailed description of this transition and its main elements). The level of reserves went from a negligible amount (NZ$20 million approx.) to around NZ$8 billion in a few months. This level was kept steady until March 2020. At the same time, the interest on reserves (called Official Cash Rate) was set equal to the interbank rate. Importantly, New Zealand did not reach the zero lower bound nor conducted QE until the Covid crisis in 2020 (where reserves supply was raised to almost NZ$30 billion), and so it is an ideal scenario to study a floor system.

Data for New Zealand provides support to the assumption that reserves supply is no longer endogenous to monetary policy under a floor system. The correlation between the interest on reserves and the supply of reserves is not significantly different from zero (for comparison, under a scarce-reserve system, the correlation between the federal funds rate and the supply of reserves is significantly negative). At the same time, in New Zealand the correlation between T-bills and reserves is also not significantly different from zero, showing the disconnection between the two under a floor system. The Appendix shows these correlations graphically. It also addresses two specific episodes in which the RBNZ injected liquidity into the banking system, which were most likely driven by liquidity concerns and therefore endogenous.

2.2 Results

I estimate Equation (4) via instrumental variables. The dependent variable is the spread between the 6-month term deposit and the 6-month T-bill. Data starts in March 2009 (the month the New Zealand Treasury started auctioning 6-months instruments) and ends in July 2021. The independent variables are the interest on reserves, the VIX index -to account for demand shifts due to uncertainty-, the supply of government debt (which I proxy by using the supply of T-bills or the supply of debt of all maturities), and the supply of deposits or reserves. The latter accounts for the few instances where the RBNZ injected reserves for endogenous reasons: the months during 2020 in which the RBNZ conducted large-scale asset purchases and two other episodes discussed in the Appendix. I use two measures of the supply of deposits: total amount taken from the RBNZ's balance sheet, and total amount taken from the households' balance sheets. Newey-West standard errors correct for autocorrelation.

For robustness, in the Appendix I run the regressions using the spread between the 90-day Bank Bill and the 3-month T-bill as a measure of the liquidity premium. It also shows robustness to estimating the regression in first-differences and to dropping the Covid pandemic months.

Instrumental variables are important since an unobserved liquidity demand shock (correlated with interest rates or the supply variables) may induce the central bank to lower interest rates in the same month, leading to reverse causality. This would result in a downwardly biased estimate of the interest rate coefficient.

To instrument the interest on reserves I use futures prices, in the same way as Piazzesi and Swanson (2008). In particular, I use the generic future contract for the 3-month bank bill, available in Bloomberg. These are futures contracts that settle at the end of each month based on the average rate that prevails during that month. The futures price before expiration is a risk-adjusted forecast of the average rate that prevails during the expiration month. Used as an instrument, the futures price in months prior to the expiration month should therefore be highly correlated with the average policy rate during the expiration month.

To instrument the supply variable, I use nonlinear functions of the ratio of total debt to GDP. Greenwood et al. (2015) and Nagel (2016) use month dummies to exploit the strong seasonality in T-bill supply in U.S. data. This arises from seasonal fluctuations in tax receipts that are plausibly exogenous and immune to the reverse causality problem. This does not seem to work for New Zealand data. Nonlinear functions of total debt to GDP, instead, exploit the positive correlation between total debt and its maturity structure. This instrument has been used, for example, in Krishnamurthy and Vissing-Jorgensen (2012).

Table 1: New Zealand: Determinants of the liquidity premium - 2SLS

	(1)	(2)	(3)	(4)
ior_t	-0.323	-0.387	-0.214	-0.217
	(0.1213)	(0.111)	(0.122)	(0.055)
$\log(\frac{Tbill}{GDP})_t$	-0.446	-0.405		
	(0.162)	(0.154)		
$\log(\frac{Debt}{GDP})_t$			-0.653	-0.498
			(0.340)	(0.276)
$\log(\frac{HHDeps}{GDP})_t$	-4.628			
	(1.058)			
$\log(\frac{Deps}{GDP})_t$		-5.881	-1.386	
		(1.259)	(1.559)	
$\log(\frac{Reserves}{GDP})_t$				-0.953
				(0.190)
vix_t	-0.00106	-0.00108	-0.0098	0.0164
	(0.0118)	(0.0128)	(0.0106)	(0.0117)
Constant	4.348	8.779	3.7411	-0.459
	(0.996)	(1.741)	(2.377)	(0.525)
Instruments for:				
IOR	Y	Y	Y	Y
Tbill/Debt supply	Y	Y	Y	Y
Deposits/Reserves	Y	Y	Y	Y
Weak instruments test				
CD stat	22.1	26	22.88	40.35
SY critical value	8.5	8.5	8.5	8.5
Observations	149	149	149	149
R-squared	0.254	0.287	0.2711	0.357

Notes: Data are at monthly frequency. Units are hundredth of basis points. Dependent variable is the 6-month Term deposit/Tbill spread. $\log(\frac{Debt}{GDP})_t$ includes outstanding government debt of all maturities. $\log(\frac{HHDeps}{GDP})_t$ are total deposits in households' balance sheet. $\log(\frac{HHDeps}{GDP})_t$ are deposits in the monetary base. Instruments for debt supply are nonlinear functions of the ratio of total debt to GDP. Instruments for the supply of deposits are nonlinear functions of the ratio of T-bills to GDP. A CD stat greater than the Stock and Yogo critical value rejects weak instruments (with bias greater than 10% of OLS bias). Newey-West standard errors in parenthesis (3 lags).

Table 1 shows the results. Columns 1 and 2 use the supply of T-bills as a measure of the supply of government debt. The coefficient on T-bill supply is negative and significant. A one percent increase in the supply of T-bills reduces the liquidity premium by between 41 and 46 basis points. This result is robust to the measure of the supply of deposits used. The magnitude is lower than in Krishnamurthy and Vissing-Jorgensen (2012) but is much larger than the non-significant effect found by Nagel (2016) for the U.S. data. Table 1 shows, unlike Nagel (2016), the effect of debt supply on the liquidity premium when the confounding factor of central bank reserves is absent.

Interestingly, the coefficient on the interest on reserves is significantly negative, which again is the opposite as in Nagel (2016). Table 1 shows the effect of the monetary policy rate stripped from its connection with the supply of central bank reserves and represents the effect of a monetary policy tightening under an ample-reserves system. This is a complete switch of the sign in the correlation between the monetary policy rate and the liquidity premium compared to a scarce-reserves system. The model in the next section will propose two channels to explain this negative effect and explore its implications. The Appendix shows that this negative coefficient also shows up for data in the U.S. after 2008, even though in that case the caveat of an endogenous supply of reserves still applies.

Columns 3 and 4 replicate the first two columns but including the supply of debt of all maturities as a proxy for the supply of government debt. Both the coefficient on the IOR and the negative effect of government debt are robust. A one percent increase in the supply of total debt reduces the liquidity premium by between 50 and 65 basis points.

Importantly, the instruments in Table 1 are strong as shown by the relatively high Cragg-Donald statistics. A statistic greater than the critical values from Stock and Yogo (2005) -also shown- rejects the hypothesis of weak instruments (with bias greater than 10% of the OLS bias) at a significance level of 5%.

3 Monetary and fiscal policy interactions

In this section, I set up a model to explore interactions between monetary and fiscal policy. The details of the model are described in the Appendix, and here I sketch the main elements. In the model the liquidity premium arises at the household level, who derive convenience services from either deposits (issued by banks) or T-bills. This is slightly different from the discussion in Section 2.1, where the premium showed up at the banks' level, which derived liquidity from reserves or T-bills. I do this because it will allow me to compare the implications with those in Nagel (2016) and Vandeweyer (2021). In addition, reserves are one of the determinants for the supply of deposits, and it is reasonable to assume that ultimately banks are just intermediaries who want to serve households. Moreover, the households combine liquidity preferences with consumption-saving decisions, which are central to monetary policy.

This is an endowment economy with households, banks, a government, and a central bank. The representative household obtains utility from consumption and a real stock of liquid assets, Q_t:

$$\mathbb{E}_0 \sum_{t=1}^{\infty} \beta^t [u(C_t) + \alpha \log(Q_t)] \tag{5}$$

$$Q_t = \left[(1-\lambda) \left(\frac{D_t}{P_t} \right)^{\rho} + \lambda \left(\frac{B_t^h}{P_t} \right)^{\rho} \right]^{\frac{1}{\rho}} \tag{6}$$

where $\frac{D_t}{P_t}$ denotes real balances of deposits and $\frac{B_t^h}{P_t}$ denotes the real value of the household's T-bill holdings. P_t is the nominal price of the consumption good. These liquidity benefits arise from some unmodeled use of liquid assets. Both deposits and T-bills have a 1-period maturity. Equation (6) is commonly used in the literature. If $\rho = 1$, T-bills and deposits are perfect substitutes. If $0 < \rho \leq 1$ they are imperfect substitutes. The parameter λ allows for differences in the relative contribution of T-bills and deposits to the stock of liquidity.

The budget constraint is:

$$\begin{aligned} &D_t + B_t^h + k_t A_t - L_t + P_t C_t = D_{t-1}(1 + i_{t-1}^d) + B_{t-1}(1 + i_{t-1}^b) \\ &+ k_{t-1}(A_t + P_t Y_t) - T_t - L_{t-1}(1 + i_{t-1}) + \Omega_t \end{aligned} \tag{7}$$

where k_t denotes the share of total endowment stream, Y_t, that the household owns at the end of period t, A_t is the price of the claim to the endowment stream, T_t denotes transfers/taxes from the government, i_t^b is the T-bill yield, i_t^d is the interest rate on deposits, L_t denotes loans, Ω_t is the flow of profits from banks to households, and i_t is the nominal interest rate applicable to assets that do not produce a liquidity service flow.

The first order condition with respect to bonds holdings is:

$$\frac{\alpha \lambda_t (\frac{B_t^h}{P_t})^{\rho-1}}{(1-\lambda_t)(\frac{D_t}{P_t})^{\rho} + \lambda_t (\frac{B_t^h}{P_t})^{\rho}} = u_c(C_t) \frac{i_t - i_t^b}{1 + i_t} \tag{8}$$

The liquidity premium is the spread between the intertemporal rate governing the consumption/savings Euler equation, i_t, and the yield on T-bills, i_t^b. The latter is lower because of the marginal utility service provided by the stock of real liquid assets (the left -hand side of (8)). The premium will depend negatively on the quantity of both T-bills and deposits. The supply of T-bills, $\frac{B_t^h}{P_t}$, follows an exogenous shock.

Deposits also have a liquidity premium, as their yield, i_t^d, trades below the intertemporal rate, i_t, as seen in deposits' first order condition:

$$\frac{\alpha (1-\lambda_t)(\frac{D_t}{P_t})^{\rho-1}}{(1-\lambda_t)(\frac{D_t}{P_t})^{\rho} + \lambda_t (\frac{B_t^h}{P_t})^{\rho}} = u_c(C_t) \frac{i_t - i_t^d}{1 + i_t} \tag{9}$$

Banks issue deposits because they are a cheaper source of funding than equity capital. However, deposits are costly to produce, and this cost is negatively related to the supply of reserves set by the central bank. However, above a certain level of outstanding reserves, $\overline{M}_t$, this cost becomes zero and banks no longer respond to the supply of reserves.

The central bank has a price level target, P^*, and follows a standard policy rule for the IOR, i_t^m. The central bank supplies enough reserves so that $M_t > \overline{M}_t$, and achieves its target solely through setting the IOR. Importantly, the interest on reserves trades below the intertemporal rate governing the Euler equation, and so the overall supply of liquid assets is a relevant input for the central bank.

How is monetary policy transmitted? An increase in the IOR (without a change in the supply of reserves and therfore on D_t on the left-hand side of (9)) increases the interest the central bank pays to banks, and banks fully pass-through this higher rate to the yield they pay on deposits to households. In turn, the increase leads to a decrease in the price level, which increases the *real* supply of liquid assets. The marginal convenience service on deposits (the left-hand side of (9)), therefore, decreases, and the intertemporal rate on the consumption's Euler equation, i_t, increases (by less than the increase in the IOR).

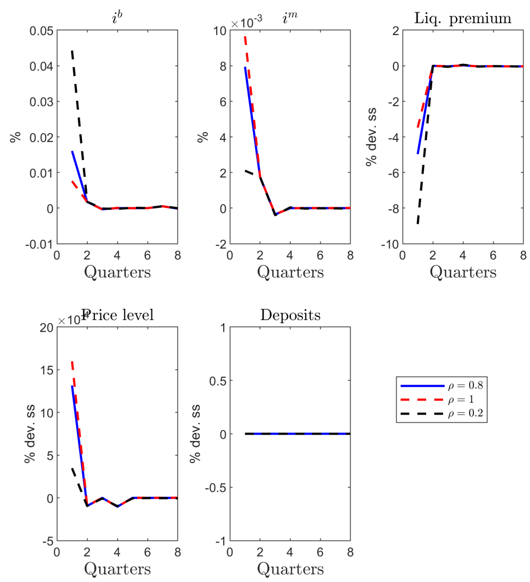
3.1 Shock to the supply of debt

First, I consider an exogenous increase in the supply of government debt. In New Zealand data, annual growth rate of the supply of T-bills between January 2008 and February 2020 has a mean of 6.25% and a standard deviation of 79. This large standard deviation is influenced by the debt issuance in response to the global financial crisis. I consider an increase in the debt to GDP ratio of 1.08% over a year. The blue line in Figure 2 compares the impulse responses of the yield on T-bills, the liquidity premium, the price level, and deposits for a value of $\rho = 0.8$.

When the government issues new debt, the monetary policy rule calls for a rise in i_t^m as the price level rises. Alternatively, from a liquidity preference perspective, the central bank has to lower the cost of liquidity of households to encourage them to hold the new debt. This is achieved through an increase in the interest on reserves, which banks pass onto the yield they pay on deposits. This will reduce the cost of liquidity for all liquid assets in the economy, including T-bills. Since in a floor system the rise in the IOR can be achieved without altering the supply of reserves, there is no change in the supply of deposits. The final effect is a drop in the liquidity premium, coming both from the direct effect of extra supply of debt and the indirect effect of the higher interest on reserves.

In Nagel (2016)'s model, the central bank would also raise the interest rate, but this would need a reduction in reserves and in the supply of deposits. This drop in the supply of deposits would offset the increase in debt supply; if they are perfect substitutes, then there would be no change

Figure 2: Positive debt supply shock - floor system



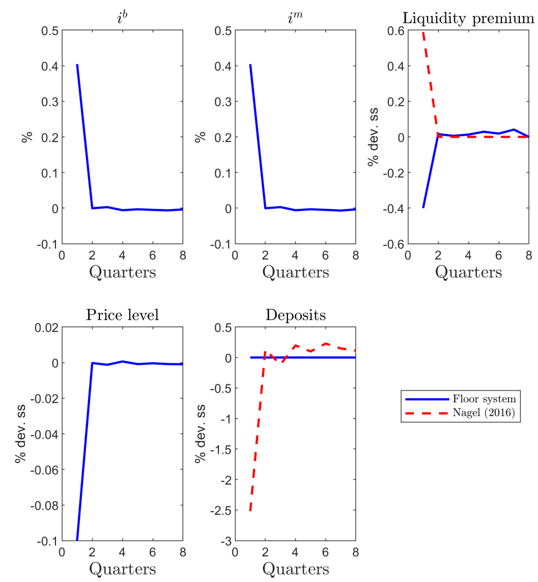
in overall liquidity and no change in the liquidity premium. This is how he explains that in his regressions the supply of debt has no statistical significance. Notice, however, that this mechanism predicts a negative correlation between debt and reserves, which does not fit the data.

Figure 2 also shows the responses for different degrees of substitutability between deposits and T-bills. I plot the responses for $\rho = 0.2$ (low substitutability between deposits and T-bills) and $\rho = 1$ (perfect substitutability) along with $\rho = 0.8$. The purpose of this Figure is to show that the supply of debt has a causal impact on the liquidity premium regardless of the degree of substitutability between deposits and bonds. Vandeweyer (2021) extends the regressions in Nagel (2016) and finds that the supply of debt has become statistically significant in the United States after 2008. This leads him to conclude that it must be because deposits and T-bills are no longer perfect substitutes. Figure 2 shows that debt becoming statistically significant once the United States transitioned to an abundant-reserve system cannot be used to conclude on the degree of substitutability between T-bills and deposits.

3.2 Shock to the IOR

In this subsection I consider an exogenous tightening of the interest on reserves. The monetary policy shock in the model is assumed to follow an iid process. The 25 basis point shock increases the interest paid on reserves, with everything else being equal, by 1% at annual rates. In Figure 3 I set the parameter ρ at 0.8, reflecting a high degree of substitutability. For the sake of comparison, the red line shows the responses in a model like in Nagel (2016).

Figure 3: Monetary Policy tightening - floor vs. scarce-reserve system



In the current model of a floor system, the hike in the interest on reserves has two effects. First, it increases the yield earned by banks on holding reserves, which they pass-through to a higher yield on deposits. This lowers the cost of liquidity for households and, therefore, their willingness to pay for the liquidity provided by T-bills. Second, it lowers the price level, increasing the real value of liquid assets for households. This, in turn, reduces the marginal value of liquidity. The combined effect of these two forces lowers the liquidity premium on T-bills, as shown by the solid blue line in Figure 3.

These two channels are absent in Nagel (2016). In his model, the sign of the effect of the policy rate (which in a corridor system is different from the interest on reserves) hinges critically on the degree of substitutability of liquid assets. This is because the hike in the policy rate is linked one-to-one with a reduction in the supply of reserves. The reduction in the supply of deposits (coming from the reduction in the supply of reserves) reduces the liquidity aggregate, Q_t. Accordingly, the liquidity premium of T-bills rises, the more the closer substitution between the two liquid assets.

Overall, this exercise shows that a monetary policy tightening can have a negative impact on the liquidity premium. This has two important implications. First, for the fiscal outlook of the government. Notice that the yield on T-bills rises along with the interest on reserves. The government is paying a higher yield and enjoying lower savings due to a lower convenience yield. Second, for monetary policy: under a scarce-reserve system, the monetary policy rate affected the liquidity premium of all liquid assets in the same direction, but under a floor system that is no longer true for the interest on reserves.

4 Conclusions

This paper has shown that the supply of government debt negatively impacts the liquidity premium. A government that borrows too much can reduce the premium and eventually exhaust it. From the perspective of fiscal policy, too much borrowing can reduce the debt revenue term in the government's budget constraint, significantly reducing its fiscal capacity (Mian et al., 2021; Reis, 2021).

I have also provided new insights on the interaction of the short-end of government bonds with monetary policy. The positive correlation between the monetary policy rate and the liquidity premium likely reverses under a floor system. As the number of advanced economies implementing an abundant-reserves system has grown, it is even more critical to understand how this new system has changed this and other linkages between monetary and fiscal policy.

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Appendix A Data sources

Yields: the interest on reserves, the 3-month bank bill rate, and the 6-month term deposit rate are from the Reserve Bank of New Zealand (RBNZ) statistics. See Wholesale interest rates, table B2 monthly, for the OCR and the bank bill, and Retail interest rates, table B3, for the term deposit rate. The 3- and 6-months yields on T-bills are calculated from auction results published by the Debt Management Office of the New Zealand's Treasury. When there is more than one instrument offered, I take the weighted average of successful yields.

Supply of T-bills and deposits: the amount of T-bills outstanding are published at the monthly frequency by the Debt Management Office of the New Zealand's Treasury. Series are at market value. The supply of reserves by the central bank is obtained from the RBNZ's balance sheet (see statistics, table R2). The two proxies for the supply of deposits correspond to households' deposits at registered banks, available at the RBNZ's statistics (see Household balance sheet, table C22); and total deposits calculated as broad money minus currency in circulation (from the RBNZ's balance sheet).

All these variables are scaled by GDP, which it is available at FRED (current price Gross Domestic Product in New Zealand, New Zealand dollars, Quarterly). The series was brought to monthly frequency through interpolation.

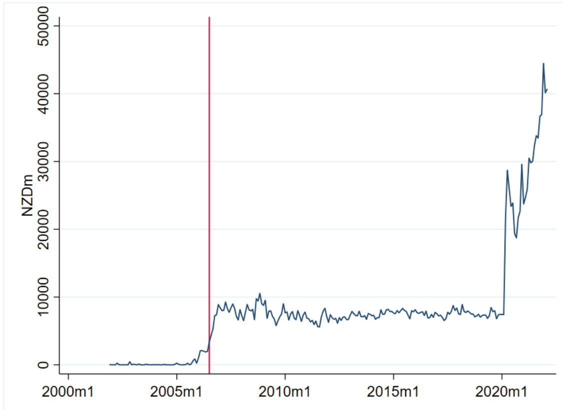
Other: the VIX index and the U.S. federal funds rate were obtained from FRED (series VIXCLS and EFFR). Data for bank bills' futures contracts prices (the instrumental variable for the IOR) was obtained from Bloomberg, tickers ZB1 and ZB2. Supply for U.S. T-bills (see Figure 1 in the main text) was obtained from Treasurydirect. U.S. deposit supply in the same Figure corresponds to the sum of checking and savings accounts in Table 4 in H.6 release (see FRED).

Appendix B Monetary policy in New Zealand

This section relies on Keister et al. (2008) and Selgin (2018) to describe New Zealand's transition to a floor system. From 1999 until July 2006, the Reserve Bank of New Zealand (RBNZ) implemented a symmetric corridor system in which the benchmark policy rate, the Official Cash Rate (OCR), was kept 25 basis points above the rate paid on reserves and 25 points below what was charged for overnight loans. Because in such a regime banks' overnight settlement balances (i.e., reserves) bore an opportunity cost, banks held very few such balances, relying instead on intraday credits from the RBNZ to meet their ongoing settlement needs.

Along with its corridor system, the RBNZ implemented a Real Time Gross Settlement (RTGS) system for wholesale payments, in which interbank payments are settled bilaterally and immediately, thereby becoming final and irrevocable as transactions are processed, rather than at the end of the business day only. This allows payments to be made final as soon as they are processed. If

Figure 4: Reserve supply in New Zealand



in the remainder of the day a bank faced any real-time liquidity need, it would rely on credit from the RBNZ instead of waiting to settle their net balances at the end of each day.

The disadvantage of the RTGS is that it exposed the central bank to credit risk. To avoid that risk the RBNZ chose to supply intraday credit through fully secured reverse repo agreements. However, the Government of New Zealand had been running a fiscal surplus for a few years and government bonds had become scarce. Since these bonds were the preferred collateral, the scarcity produced wide volatility in the interbank market and often resulted in rates significantly above the target desired to implement monetary policy. The RBNZ had to accept municipal and corporate paper as collateral, which did not fully eliminate risk of losses.

The RBNZ conducted a review of its liquidity management regime in 2005 and announced a new system in early 2006. Recognizing the danger of losses, the RBNZ encouraged banks to rely on overnight settlement balances (reserves), instead of intraday repos, to meet their settlement needs. With that end in mind, in July 2006 the RBNZ began its program of "cashing up" the banking system. The first step was to create an additional NZ$7 billion in reserves between July and October. Concurrently, it increased the interest paid on those reserves in 25 basis points (made in five-points increments), to encourage banks to hold them. Next, the RBNZ stopped providing intraday repos. At the end, the RBNZ achieved the two key components of a floor system: the interest rate on reserves was set equal to the policy rate and banks were well supplied, if not satiated, with liquidity.

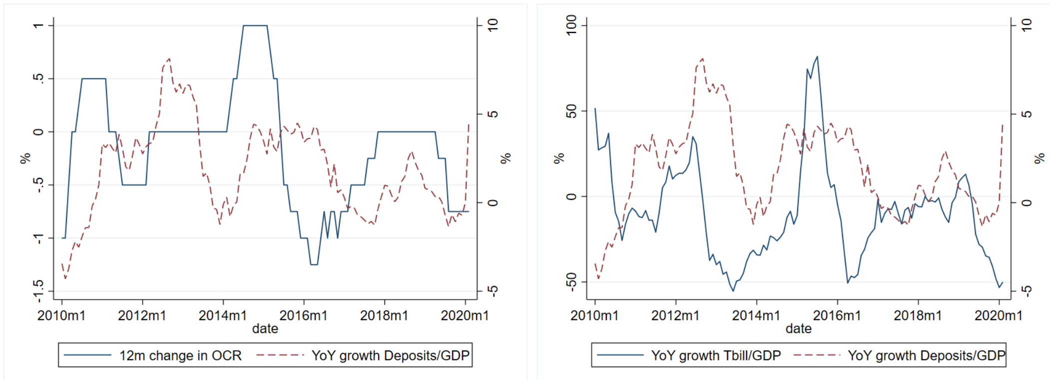
Figure 4 plots the evolution of the supply of reserves. The vertical red line marks the official start of the floor system. The level of reserves went from a negligible amount (NZ$20 million approx.) to around NZ$8 billion. This level was kept steady until March 2020, when QE raised the supply to almost NZ$30 billion.

Figure 5 suggests that deposit supply is no longer endogenous to monetary policy under a floor system. Banks hold enough reserves, and the liquidity cost of creating new deposits no longer

Figure 5: Correlations for NZ: Jul. 2006 - Feb. 2020

(a) Interest on reserves and deposit supply

(b) T-bills and deposit supply



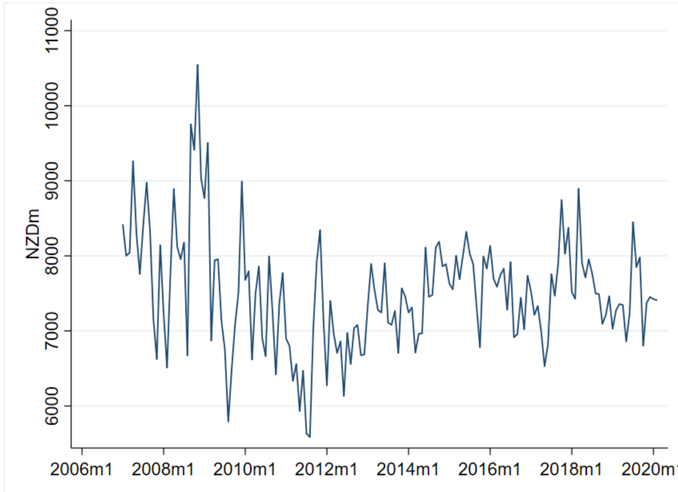
depends on the availability of reserves. In Figure 5a the correlation between the interest on reserves and the supply of deposits is not significant. Under a corridor system like the one in the United States before 2008, this correlation would be significantly negative. In Figure 5b the correlation between T-bills and deposits is also not significantly different from zero, showing the disconnection between the two under a floor system.

Can we be sure to rule out any endogenous variation in reserve supply? There are two episodes in which the RBNZ injected further liquidity into the banking system, both during the financial turmoil of 2008 (in August 2007 and in the Fall of 2009). These are the most likely to be driven by liquidity concerns and thus be endogenous. Figure 6 provides a closer inspection for the evolution of reserve supply. Although the RBNZ occasionally found it desirable to inject some extra reserves into the banking system -as in the two episodes mentioned- those cash additions were modest and transitory. As an extra precaution, I add the supply of reserves or deposits in the regressions, in order to control for any out-of-order variation in their quantities.

Finally, one important reform happened in August 2007. A common issue with supplying too many reserves is that banks no longer need to rely on one another to access reserves, effectively ending active trading in the interbank market. This is what has happened in the US since 2008 in the federal funds market, were the number of transactions has been at a minimum for the past decade. The RBNZ concluded that it was a good idea to avoid this outcome, as an active interbank market provides information on the health of the banks. However, once the floor system was up and running it became clear that it was encouraging at least some banks to hoard reserves, accumulating them without incurring any opportunity cost and thus without the need to go to the interbank market.

The solution to the reserve hoarding problem was a “tiering system”, with reserves up to a bank’s assigned tier limit earning the interest on reserves, and reserves beyond that level earning 100 basis points less. The tier levels were themselves based on banks’ apparent settlement needs,

Figure 6: Correlations for NZ: Jul. 2006 - Feb. 2020



but collectively still amounting to the aggregate target of NZ$7 billion. Thanks to this switch to a tiered system, the overnight interbank lending market remained active. Banks continued to rely upon one another as lenders of first resort, turning to the RBNZ for overnight funds only as a last resort.

It is important to notice that this tiered system does not affect my identification strategy. Even though an active interbank market might suggest that banks are not fully satiated with liquidity, my strategy only needs that the overall supply of reserves is not correlated with the monetary policy rate, as they actually are in a scarce-reserve system. Figure 5 shows that this is the case. In contrast, the same graph for a corridor system -like the one in the US before 2008- would show a significant negative correlation between the federal funds rate and the supply of reserves/deposits.

Appendix C Robustness for results in section 2

Table 3 estimates equation (4) with data for New Zealand, from July 2006 until July 2021. The dependent variable is the spread between the 3-month bank bill and the 3-month T-bill. To avoid concerns with stochastic trends I difference both the dependent and the independent variables. This avoids spurious correlation between the levels of these variables by removing random walk components in these series. All columns are estimated using OLS, with the standard errors adjusted for autocorrelation using the Newey West estimator.

In Column 1 the coefficient on the supply of T-bills is negative and significant. A one percent increase in T-bills to GDP reduces the liquidity premium in 28 basis points. The coefficient on the IOR is negative, although not statistically significant. Column 2 adds the supply of reserves as a percentage of GDP, which serves as a robustness check to the intuition that under a floor system reserves supply are exogenous in the determination of the liquidity premium. The estimation shows

Table 2: New Zealand: Determinants of liquidity premium - OLS

	Sample: 2006m7-2021m7				Sample: 2006m7-2020m2			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δior_t	-0.0826	-0.0835	-0.187	-0.187	-0.0941	-0.101	-0.206	-0.227
	(0.0520)	(0.0529)	(0.0629)	(0.0630)	(0.0558)	(0.0542)	(0.0685)	(0.0697)
Δior_{t-1}			0.265	0.269			0.273	0.295
			(0.0763)	(0.0749)			(0.0774)	(0.0812)
Δvix_t	0.00352	0.00256	0.00157	0.000450	0.00477	0.00459	0.00353	0.00370
	(0.00133)	(0.00166)	(0.00149)	(0.00203)	(0.00193)	(0.00175)	(0.00216)	(0.00203)
Δvix_{t-1}			0.00134	0.000670			-0.000563	-0.000823
			(0.00449)	(0.00480)			(0.00641)	(0.00629)
$\Delta\log(\frac{Tbill}{GDP})_t$	-0.278	-0.290	-0.193	-0.195	-0.371	-0.349	-0.299	-0.284
	(0.124)	(0.119)	(0.0922)	(0.0767)	(0.188)	(0.184)	(0.117)	(0.108)
$\Delta\log(\frac{Tbill}{GDP})_{t-1}$			-0.0475	-0.0419			-0.0676	-0.0538
			(0.0901)	(0.0885)			(0.119)	(0.109)
$\Delta\log(\frac{Res}{GDP})_t$		0.119		0.139		0.180		0.218
		(0.0855)		(0.114)		(0.135)		(0.145)
$\Delta\log(\frac{Res}{GDP})_{t-1}$				-0.00894				-0.129
				(0.0795)				(0.0927)
Constant	-0.00646	-0.00786	-0.000266	-0.00158	-0.00864	-0.00947	-0.00253	-0.00259
	(0.00810)	(0.00833)	(0.00599)	(0.00624)	(0.0101)	(0.0103)	(0.00716)	(0.00704)
Observations	181	181	181	181	164	164	164	164

Notes: Newey-West standard errors in parentheses (6 lags). Units are hundreds of basis points. Dependent variable is the first difference of the 3-month Bank bill/T-bill spread. Independent variables are the same as in Table 1 in the main text.

that it does not have a significant effect, and the coefficient on the supply of T-bills is similar in magnitude and significance.

In columns 3 and 4 I add the current and lagged values of the independent variables. I do this to consider the possibility that the coefficients in columns 1 and 2 are only capturing a transitory effect on the liquidity premium. This is especially relevant in this case where I am using 1-month differences. It can be the case, for example, that new debt issuance by the government has a short-lived impact that fades away soon after (this is in fact what Nagel (2016) find for the supply variable in the US). Results show that the supply of T-bills still has a negative and significant impact, although of smaller magnitude. Importantly, and unlike the results in Nagel (2016), the lagged value is not significant, suggesting it has a more persistent effect. The results for the IOR are the opposite. The current value of the IOR has a significant negative impact that almost fully reverts in the following month. The negative effect of the IOR and its transitory nature is the opposite result as the one in Nagel (2016).

In columns 5-8 I replicate the first four columns but with the sample ending in February 2020. Recall that the RBNZ embarked in large scale asset purchases after March 2020. Large scale asset purchases involve the purchase of assets in exchange of newly issued reserves. Therefore, in this situation we should not expect the supply of reserves to be exogenous anymore. The estimation in columns 5-8 serves as a robustness check as it should be free of any effect of QE and the possible endogeneity of the supply of reserves. The results show that the effects of the supply of T-bills and the IOR are still significant.

Appendix D Regressions with U.S. data after 2008

Is the negative effect of the interest on reserves robust to using data for other countries? The following Table shows regressions of the liquidity premium for the U.S. after November 2008. The dependent variable is the spread of 3-month AA financial commercial paper and 3-month T-bills. Data for T-bill and reserve supply are from Treasurydirect and FRED, respectively. The caveats pointed out in the main text still apply: mainly, that the supply of reserves is likely to be endogenous to the different QE programs carried out by the Federal Reserve between 2009-2014. However, it is interesting to see the coefficients for the IOR and the supply of T-bills are of the same sign as in Table 3. In particular, both the interest on reserves and the supply of T-bills have a negative effect on the liquidity premium. These results are robust to using IVs (not shown).

Appendix E Model

It is an endowment economy-representative agent model comprised of households, who have a special demand for liquid assets (deposits and T-bills); a financial sector (banks, for short) who provide deposits by accumulating central bank reserves and other assets; a fiscal authority who every period supplies liquid securities; and a central bank that conducts monetary policy who targets a price level. I choose to rely on a monetary model with flexible prices as it better highlights the role of liquidity premia for both the central bank and the government.

E.1 Households

This sector follows Nagel (2016) closely, which will facilitate comparisons with his results. There is a single perishable consumption good with endowment stream $\{Y_t\}$. The endowment follows an exogenous process:

$$\log Y_{t+1} = \rho_y Y_t + \epsilon_{t+1} \quad , \epsilon_t \sim N(0, \sigma^2) \tag{10}$$

Table 3: U.S.: Determinants of liquidity premium, 2008m11-2020m6 - OLS

	(1)	(2)	(3)	(4)
Δioer_t	-0.363	-0.604	-0.361	-0.511
	(0.124)	(0.158)	(0.157)	(0.124)
Δioer_{t-1}			0.449	0.403
			(0.131)	(0.103)
Δvix_t	0.0131	0.0119	0.0113	0.00813
	(0.00293)	(0.00246)	(0.00284)	(0.00198)
Δvix_{t-1}			0.00561	0.00453
			(0.00184)	(0.00181)
$\Delta\log(\frac{Tbill}{GDP})_t$	-0.895	-0.755	-0.498	-0.625
	(0.223)	(0.195)	(0.139)	(0.154)
$\Delta\log(\frac{Tbill}{GDP})_{t-1}$			0.266	0.371
			(0.167)	(0.123)
$\Delta\log(\frac{Res}{GDP})_t$		-0.932		0.0747
		(0.343)		(0.167)
$\Delta\log(\frac{Res}{GDP})_{t-1}$				-0.495
				(0.169)
Constant	-0.0127	-0.00209	-0.00442	2.91e-05
	(0.0137)	(0.00935)	(0.00516)	(0.00464)
Observations	140	140	139	139

Notes: Newey-West standard errors in parentheses (6 lags). Units are hundreds of basis points. Dependent variable is the first difference of the 3-month AA financial commercial paper/T-bill spread.

The representative household seeks to maximize the objective:

$$\mathbb{E}_0 \sum_{t=1}^{\infty} \beta^t [u(C_t) + \alpha \log(Q_t)] \tag{11}$$

where C_t is consumption and Q_t is a real stock of liquid assets that the household draws service flows from. Liquidity services are supplied by money in the form of demand deposits and near-money in the form of T-bills issued by the government. Stock of liquidity is the CES aggregate:

$$Q_t = \left[(1-\lambda_t) \left(\frac{D_t}{P_t} \right)^{\rho} + \lambda_t \left(\frac{B_t^h}{P_t} \right)^{\rho} \right]^{\frac{1}{\rho}} \tag{12}$$

where $\frac{D_t}{P_t}$ denotes real balances of deposits and $\frac{B_t^h}{P_t}$ denotes the real value of the household's T-bill holdings. P_t is the nominal price of the consumption good. These liquidity benefits arise from some unmodeled use in intra-period transactions. A model period is one quarter, and T-bills have a one-period maturity.

The parameter ρ controls the elasticity of substitution between T-bills and deposits. With $\rho = 1$, T-bills and deposits are perfect substitutes, and the composition of the aggregate liquidity supply is irrelevant. If they are imperfect substitutes, then $0 < \rho \leq 1$. The parameter λ, allows for differences in the relative contribution of T-bills and deposits to the stock of liquidity.

Households optimize subject to the flow budget constraint:

$$\begin{aligned} D_t + B_t^h + k_t A_t - L_t + P_t C_t &= D_{t-1}(1 + i_{t-1}^d) + B_{t-1}(1 + i_{t-1}^b) \\ &+ k_{t-1}(A_t + P_t Y_t) - T_t - L_{t-1}(1 + i_{t-1}) + \Omega_t \end{aligned} \tag{13}$$

where B_t^h are the holdings of T-bills. k_t denotes the share of total endowment stream that the household owns at the end of period t, A_t is the price of the claim to the endowment stream, T_t denotes transfers/taxes from the government, i_t^b is the T-bill yield, i_t^d is the interest rate on demand deposits, L_t denotes loans, Ω_t is the flow of profits from banks to households, and i_t is the nominal interest rate applicable to assets and transactions that do not produce a liquidity service flow.

The household first-order condition with respect to consumption yields the intertemporal Euler equation

$$1 + i_t = \frac{1}{\beta} \left\{ \mathbb{E}_t \left[\frac{u_c(C_{t+1})}{u_c(C_t)} \frac{P_t}{P_{t+1}} \right] \right\}^{-1} \tag{14}$$

where u_c denotes the first derivative of $u(.)$. Equation (14) governs the household's intertemporal decisions, and thus this is the rate that the monetary authority is looking to affect. However, as explained below, the central bank's policy rate is the rate on deposits, which will carry a convenience yield and will trade below the i_t.

The first-order conditions with respect to real liquid asset balances are:

$$\frac{\alpha(1-\lambda_t)(\frac{D_t}{P_t})^{\rho-1}}{(1-\lambda_t)(\frac{D_t}{P_t})^{\rho} + \lambda_t(\frac{B_t^h}{P_t})^{\rho}} = u_c(C_t)\frac{i_t - i_t^d}{1+i_t} \tag{15}$$

$$\frac{\alpha\lambda_t(\frac{B_t^h}{P_t})^{\rho-1}}{(1-\lambda_t)(\frac{D_t}{P_t})^{\rho} + \lambda_t(\frac{B_t^h}{P_t})^{\rho}} = u_c(C_t)\frac{i_t - i_t^b}{1+i_t} \tag{16}$$

Equation (15) reflects the valuation of inside money, or deposits, by households. I assume households rely on deposits to make transactions and are therefore willing to accept an interest rate on deposits i_t^d that is below the intertemporal rate. The opportunity cost of money $i_t - i_t^d$ reflects the value of money for making payments. It is declining in real balances: the marginal benefit of payment instruments is declining in the overall quantity held. Equation (16) reflects that, for households, bonds might serve the same purpose as deposits.

E.2 Banks

The representative bank in this economy exists because households cannot access central bank's reserves directly. The bank therefore originates liquid deposits by either holding assets or by holding reserves at the central bank. Specifically, I assume banks take deposits, on which they promise to pay a riskless nominal return i_t^d one period later and hold other assets (such as loans) on which they earn a nominal interest rate of i_t. They also choose a quantity of reserves M_t^d to hold at the central bank on which they will receive a nominal yield of i_t^m. The bank takes all these interest rates as given.

Banks face liquidity shocks because their debt is inside money used by households for transactions. Reserves are more useful for handling liquidity shocks than other assets: if they are sufficiently scarce, banks are willing to pay a higher price. This is the demand curve that many central banks exploited before 2008: they targeted a positive spread between the interbank rate and the reserve rate (which was zero in the case of the US), and elastically supplied reserves to achieve that spread.

The bank will consume real resources $\theta(\frac{\zeta_t D_t^s}{M_t^d})$, where $\theta_D > 0$, $\theta_M < 0$ and $\theta_D = \theta_M = 0$ for $M_t^d \geq \overline{M}_t$. This specification resembles the banks' demand for reserves in the model of Poole (1968) and Afonso et al. (2020). This tries to capture that liquidity costs are increasing in deposits (higher chance of unexpected withdrawals and greater precautionary liquidity demand), decreasing in reserves (as they meet regulatory requirements and facilitate intraday operations), and that with a sufficiently large amount of reserves, reserve demand by banks becomes flat once they are above their reserve requirements and above their precautionary demand level, $\overline{M}_t$. ζ_t is the average propensity to use deposits for payments, which I assume to be a negative function of overall endowment Y_t.

Lastly, banks can issue deposits if they have sufficient collateral to back them:

$$D_t^s \leq M_t^d + \rho_L L_t^s \qquad \rho_L < 1 \tag{17}$$

The parameter $\rho_L < 1$ captures the fact that reserves are better collateral than other assets. Similar to Piazzesi et al. (2021) and Benigno and Benigno (2021), this constraint can be interpreted as a capital requirement. From the households' Euler equation, deposits provide a convenience yield whenever the supply of real balances is finite. It follows that, from the perspective of the bank, deposits represent a source of funding that is strictly cheaper than equity, which must earn the illiquid rate i_t. Without a leverage constraint, it would be optimal to fund the bank entirely with deposits. The leverage constraint will thus bind in equilibrium.

Banks' cash flow is given by:

$$\begin{aligned}\Omega_t = D_t^s - D_{t-1}^s(1 + i_{t-1}^d) + M_{t-1}^d(1 + i_{t-1}^m) - M_t^d + \\ L_{t-1}^s(1 + i_{t-1}) - L_t^s - \theta(M_t^d, D_t^s; \zeta_t)\end{aligned} \tag{18}$$

Banks' cash flows are discounted at the households' illiquid rate, i_t. Let γ_t be the multiplier on the leverage constraint. The maximization of the present value of cash flows is given by:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \left\{ \left(\frac{1}{1+i_t} \right)^t \Omega_t + \gamma_t (M_t^d + \rho_L L_t^s - D_t^s) \right\} \tag{19}$$

The first order conditions with respect to reserves and deposits are, thus:

$$\frac{i_t - i_t^m}{1+i_t} = \gamma_t - \theta_{Mt} \tag{20}$$

$$\frac{i_t - i_t^d}{1+i_t} = \gamma_t + \theta_{Dt} \tag{21}$$

The left-hand side of Equation (20) shows the marginal cost of an extra reserve: the forgone interest with respect to other assets. The right-hand side is the marginal benefit: a looser collateral constraint and a lower liquidity cost (as $\theta_{Mt} < 0$). The left-hand side of Equation (21) is the marginal benefit of an extra deposit: cheaper funding due to the special demand by households. The right-hand side shows the marginal cost: a tighter collateral constraint and a larger liquidity cost ($\theta_{Dt} > 0$).

By subtracting equation (21) from equation (20) I obtain the spread between the rate on deposits and the rate on reserves:

$$\frac{i_t^d - i_t^m}{1+i_t} = \begin{cases} -\theta_{mt} - \theta_{dt} & \text{if } M_t^d < \overline{M}_t, \\ 0 & \text{otherwise} \end{cases} \tag{22}$$

where recall that $\theta_{mt} \leq 0$. For $M_t^d < \overline{M}_t$, equation (22) delivers a one-to-one relationship between the supply of reserves and the policy rate. An increase in the supply of reserves reduces the liquidity cost of banks (right hand side of the equation) and thus reduces the premium on reserves, reducing i_t^d (in the left hand-side). If $M_t^d \geq \overline{M}_t$, then $\theta_D = \theta_M = 0$ and the policy rate equals the interest on paid on reserves.

The choice of i_t^d as the central bank's policy rate can be justified as follows. In reality, the Fed sets the federal funds rate, which is the rate at which banks trade reserve balances intraday among themselves. The federal funds rate can, therefore, be seen as the rate at which banks can obtain liquid funding whenever needed. Although in the model there is no interbank market, the policy rate i_t^d captures the same idea: it is the rate at which banks can obtain liquid funding, but in this case from households. Introducing a more formal interbank market and a more realistic federal funds rate would complicate the model without improving the exposition of the underlying mechanisms.

E.3 Government and Central Bank

I introduce a government in the simplest way possible. Every period, it raises taxes from the household and supplies new debt issuance. Its flow budget constraint is given by:

$$B_t^s = (1 + i_{t-1}^b)B_{t-1}^s - T_t - T_t^{cb} \tag{23}$$

where B_t^s is total debt issued, T_t are tax/transfers to the household, and T_t^{cb} are transfers from the central bank.

The central bank buys government bonds and pays with the issuance of reserves to the banking system. Its budget constraint is:

$$M_t^s + (1 + i_{t-1}^b)B_{t-1}^{cb} = B_t^{cb} + M_{t-1}^s(1 + i_{t-1}^m) - T_t^{cb} \tag{24}$$

where M_t^s is the supply of reserves and B_t^{cb} are its holdings of government bonds. Notice that $B_t^s = B_t^h + B_t^{cb}$, and therefore the budget constraint for the consolidated public sector (government and central bank) is:

$$B_t^h + M_t^s = (1 + i_{t-1}^b)B_{t-1}^h + M_{t-1}^s(1 + i_{t-1}^m) - T_t \tag{25}$$

I assume that fiscal policy is set in real terms. A shown in Canzoneri and Diba (2005), this is necessary to achieve local determinacy in nominal variables. The real supply of bonds, B_t^s/P_t, will follow an exogenous path. Taxes/transfers adjust so the budget constraint holds every period. This is a simplification, as it is likely that the maturity structure of government debt is not exogenous to the stance of monetary policy. However, this simple modeling will deliver sharp intuitions and contrasts with the existing literature.

E.4 Monetary policy implementation

The monetary authority conducts monetary policy to meet an interest rate operating target, i_t^{d*}, according to the policy rule

$$i_t^{d*} = \psi \left(\frac{P_t}{P_t^*} \right)^{\psi_\pi} e^{\xi_t} \tag{26}$$

where P_t^* represents a target path for the price level and ξ_t is an exogenous random shock. This policy rule does not consider the possibility of a zero lower bound, as the calibration for New Zealand in the period before 2020 will not involve such episodes.

I further assume that:

$$i_t^m \geq 0 \tag{27}$$

which can be rationalized by the existence of cash, in addition to deposits and T-bills: in this case, the interest paid on reserves and deposits will not fall below the rate paid by cash, which is zero. I consider the economy to be in the cashless limit and refrain from explicitly introducing cash into the model.

The central bank has three instruments at its disposal: the policy rate, i_t^d, the interest it pays on its reserves, i_t^m, and the supply of reserves to banks, M_t^s. Under a corridor or scarce-reserve system ($M_t^s < \overline{M}_t$), given an interest on reserves (zero in the case of the US before 2008), there is only one level of the supply of reserves that achieves the target for i_t^d, through equation (22). As a result, the supply of reserves is not an independent tool.

I model the implementation of the floor system as the central bank setting $M_t^s > \overline{M}_t$ at all times. Therefore, by equation (22), $i_t^d = i_t^m$ and every period teh central bank sets the interest on reserves, i_t^m. The supply of reserves becomes an independent tool as long as $M_t^s > \overline{M}_t$. To keep things simple, I assume the supply of reserves M_t^s follows an exogenous random path that never falls below $\overline{M}_t$. This exogenous shock tries to represent random demand by households due to unexpected liquidity needs (change in precautionary demand or unexpected liquidity withdrawals by households). Besides this shock, the central bank does not endogenously set M_t^s.

This is a simple representation of how the Fed has conducted monetary policy since 2008. The interest rate on reserves and the federal funds rate are the tools used to reach its goals of inflation and unemployment, and the supply of reserves is not followed closely. Indeed, the Fed's January 2019 statement reads: "*The Committee intends to* ***continue*** *to implement monetary policy* ***in a regime in which an abundant supply of reserves*** *ensures that control over the level of the federal funds rate and other short-term interest rates is exercised primarily through the setting of the Federal Reserve's administered rates, and in which* ***active management of the supply of reserves is not required*** *(...).The Committee continues to view changes in the target range for the federal funds rate as its* ***primary means*** *of adjusting the stance of monetary policy*" (emphasis is mine).

Under this system, monetary policy outside the ZLB no longer works through the supply of reserves by banks. Since banks face no liquidity cost, adjustments in the policy rate i_t^m only work through the households' cost of liquidity. Imagine there is an increase in liquidity demand (for instance, an exogenous increase in α in the model). The convenience yield of deposits will increase (left hand side of (15)). The central bank will respond by easing monetary policy: lowering i_t^m. This increases the household's cost of liquidity, $i_t - i_t^m$, on the right-hand side. Intuitively, since monetary policy no longer works through the supply of reserves, it can only respond through the household's cost of liquidity: facing an increase in demand for liquidity (bigger α), it increases the cost of it for households, $i_t - i_t^m$.

It is helpful to consider what would happen were the central bank not to react. The increase in the convenience yield of deposits would result instead in an increase in the intertemporal rate, i_t. This would also increase the household's cost of liquidity, $i_t - i_t^m$, but at the same time it would result in a drop in the price level, leading the central bank to miss its target.

It might seem counterintuitive that the central bank eases monetary policy by actually *increasing* the cost of liquidity. To understand this, notice the distinction between the household's cost of liquidity and the bank's cost of liquidity. Under a corridor system, monetary policy works mainly through the bank's cost of liquidity: an easing of monetary policy *reduces* the cost of liquidity of banks, thus increasing the *supply* of deposits. This is how we usually understand monetary policy: central banks reduce the policy rate to reduce the cost of liquidity in the economy. In a floor system, on the other hand, banks are satiated and face no cost of liquidity. Monetary policy works only through the household's cost of liquidity, which affects the *demand* for deposits, not their supply. To respond to an increase in demand the central bank can only cool it off by *increasing* the household's cost of liquidity. This in addition explains the negative sign of the coefficient on the interest on reserves in the regressions using New Zealand data.

To sum up, the main differences with respect to Nagel (2016)'s is that in his model there is no satiation with reserves, and so changes on the supply of reserves always have an effect. Moreover, the central bank's monetary policy rate coincides with the rate governing the intertemporal consumption decision. Therefore, the central bank is always offsetting new debt issuance to achieve the optimal consumption decision, and changes in the supply of reserves achieve the consumption-saving equilibrium. In addition, that model is money-neutral, meaning that the price level is governed by consumption dynamics and the response by the central bank makes it independent of the supply of liquidity.

Definition: An equilibrium in this economy are prices $\{i_t, i_t^b, i_t^m, A_t, P_t, \gamma_t\}$ and policy rules $\{C_t, D_t, B_t^h, D_t^s, B_t^s\}$ such that:

1. Given prices, households maximize lifetime utility, banks maximize future cash flows,
2. All markets clear: $k_t = 1$, $D_t = D_t^s$, $B_t^h = B_t^s$.

I solve the model using the global nonlinear method in Cao et al. (2023).

E.5 Calibration

The model is calibrated with data for New Zealand at quarterly frequency, using the sample 2006:III to 2021:III. Panel A of Table 4 shows the parameters calibrated externally. I pick a value of risk aversion of 1.5, and assume a Taylor rule parameter for inflation of 1.5, as it is common in the literature.

The rest of the parameters are calibrated under a deterministic steady state. Table 4, Panel B, shows the values for the five parameters. The targets are the illiquid rate, for which I use the yield on 6-month term deposits, the average yield on T-bills, and the OCR during the sample period. I complement this with two quantities: government debt and banking deposits. I define a supply of government debt to GDP of 0.42 (OECD data, General Government debt) and for deposits I set reserves to GDP at 0.12 and other assets to GDP at 1.4. The ratio of reserves to GDP is obtained from the RBNZ and the supply of other assets matches domestic credit by the banking sector from OECD statistics.

Table 4: Calibration

	Description	Value	Source
	A. Externally calibrated		
γ	Risk aversion	1.5	Standard
ρ_L	Collateral value of other assets	0.8	
ψ_π	CB's response function	1.5	Standard
	B. Calibrated		
β	Discount factor	0.989	
α	Liq. preference	0.0012	
λ	T-bill preference	0.4656	
ψ	CB's response function	1.0084	
P^*	Price level target	1.9727	

Notes:

The calibration exercise gives a discount factor of 0.989, which is somewhat lower than usual. However, this difference accounts for the illiquidity of the intertemporal rate in the model. The liquidity preference in the household's utility function, α, takes the value of 0.0012, and the relative usefulness of government debt, λ, is equal to 0.4659. This implies that deposits are only slightly more liquid than T-bills.

Table 5 shows how the model matches the targets for prices (quantities are exogenous in the model and are trivially matched). Last row computes the liquidity premium on government debt.

Table 5: Model moments and Targets

Variable	Description	Data	Model
i_t	Illiquid rate	4.44%	4.36%
i_t^b	Debt yield	3.25%	2.96%
i_t^m	Interest on reserves (OCR)	3.34%	3.44%
$i_t - i_t^b$	Liquidity premium	1.19%	1.40%

Notes:

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