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Abstract

We provide empirical evidence of a novel liquidity-based transmission mechanism through which monetary policy influences asset markets, develop a model of this mechanism, and assess the ability of the quantitative theory to match the evidence.

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1 Introduction

In most modern economies, central banks implement monetary policy indirectly, by intervening in certain financial markets (e.g., in the United States, the federal funds market and the market for treasury securities). The underlying idea is that the effects of those interventions on asset prices are transmitted to the rest of the economy to help achieve the ultimate policy objectives. Thus, the transmission mechanism of monetary policy to asset prices is important for understanding how monetary policy actually operates.

In this paper, we conduct an empirical, theoretical, and quantitative study of the effects of monetary policy on financial markets in general and the equity market in particular. We make three contributions. First, we provide original empirical evidence of a novel channel through which monetary policy influences financial markets: tight money increases the opportunity cost of holding the nominal assets used routinely to settle financial transactions (e.g., bank reserves, money balances), making these payment instruments scarcer. In turn, this scarcity reduces the resalability of financial assets, and this increased illiquidity leads to a reduction in price. We label this mechanism the *turnover-liquidity (transmission) mechanism (of monetary policy)*. Second, to gain a deeper understanding of this mechanism, we develop a theory of trade in financial over-the-counter (OTC) markets (that nests the competitive benchmark as a special case) in which money is used as a medium of exchange in financial transactions. The model shows how the details of the market microstructure and the quantity of money shape the performance of financial markets (e.g., as gauged by standard measures of market liquidity), contribute to the determination of asset prices (e.g., through the resale option value of assets), and—consistent with the evidence we document—offer a liquidity-based explanation for the negative correlation between real stock returns and unexpected increases in the nominal interest rate that is used to implement monetary policy. Third, we bring the theory to the data. We calibrate a generalized version of the basic model and use it to conduct quantitative theoretical exercises designed to assess the ability of the theory to match the empirical effects of monetary policy on asset prices, both on policy announcement days and at longer horizons.

The rest of the paper is organized as follows. Section 2 presents the basic model. It considers a setting in which a financial asset that yields a dividend flow of consumption goods (e.g., an equity or a real bond) is demanded by investors who have time-varying heterogeneous valuations for the dividend. To achieve the gains from trade that arise from their heterogeneous

valuations, investors participate in a bilateral market with random search that is intermediated by specialized dealers who have access to a competitive interdealer market. In the dealer-intermediated bilateral market, which has many of the stylized features of a typical OTC market structure but also nests the perfectly competitive market structure as a special case, investors and dealers seek to trade the financial asset using money as a means of payment. Periodically, dealers and investors are also able to rebalance their portfolios in a conventional Walrasian market. Equilibrium is characterized in Section 3. Section 4 presents the main implications of the theory. Asset prices and conventional measures of financial liquidity (e.g., spreads, trade volume, and dealer supply of immediacy) are determined by the (real) quantity of money and the details of the microstructure where the asset trades (e.g., the degree of market power of dealers and the ease with which investors find counterparties). Generically, asset prices in the monetary economy exhibit a speculative premium whose size varies systematically with the market microstructure and the monetary policy stance. For example, a high anticipated opportunity cost of holding money reduces equilibrium real balances and distorts the asset allocation by causing too many assets to remain in the hands of investors with relatively low valuations, which depresses real asset prices.

Section 5 is empirical. In it we revisit the finding, documented in previous empirical work, that surprise increases in the nominal policy rate cause sizable reductions in real stock returns on announcement days of the Federal Open Market Committee (FOMC). A 1 basis point unexpected increase in the policy rate causes a decrease of between 5 and 11 basis points in the stock market return on the day of the policy announcement. In addition, this section contains two new empirical findings. First, we document that episodes of unexpected policy tightening are also associated with large and persistent declines in stock turnover. Second, we find evidence that the magnitude of the reduction in return caused by the policy tightening is significantly larger for stocks that are normally traded more actively, e.g., stocks with higher turnover rates. For example, in response to an unexpected increase in the policy rate, the announcement-day decline in the return of a stock in the 95th percentile of turnover rates is about 2.5 times larger than that of a stock in the 5th percentile. The empirical evidence in this section suggests a mechanism whereby monetary policy affects asset prices through a reduction in turnover liquidity.

In Section 6 we formulate, calibrate, and simulate a generalized version of the basic model and use it to assess the ability of the theory to fit the empirical evidence on the effects of

monetary shocks on aggregate stock returns as well as the new cross-sectional evidence on the turnover-liquidity transmission mechanism. Section 7 concludes. Appendix A contains all proofs. Appendices B, C, D, and E, contain supplementary material. Appendix B covers technical aspects of the data, estimation, and simulation. Appendix C contains additional theoretical derivations and results. Appendix D verifies the robustness of the empirical and quantitative findings. This paper is related to four areas of research: search-theoretic models of money, search-theoretic models of financial trade in OTC markets, resale option theories of asset price bubbles, and an extensive empirical literature that studies the effects of monetary policy on asset prices. Appendix E places our contribution in the context of all these literatures.

2 Model

Time is represented by a sequence of periods indexed by $t = 0, 1, \dots$. Each period is divided into two subperiods where different activities take place. There is a continuum of infinitely lived agents called *investors*, each identified with a point in the set $\mathcal{I} = [0, 1]$. There is also a continuum of infinitely lived agents called *dealers*, each identified with a point in the set $\mathcal{D} = [0, 1]$. All agents discount payoffs across periods with the discount factor $\beta \equiv 1/(1+r)$, where $r > 0$ denotes the real interest rate. In every period, there is a continuum of active production units with measure $A^s \in \mathbb{R}_{++}$. Every active unit yields an exogenous *dividend* $y_t \in \mathbb{R}_+$ of a perishable consumption good at the end of the first subperiod of period t . (Each active unit yields the same dividend as every other active unit, so $y_t A^s$ is the aggregate dividend.) At the beginning of every period, every active unit is subject to an independent idiosyncratic shock that renders it permanently unproductive with probability $1 - \delta \in [0, 1]$. If a production unit remains active, its dividend in period t is $y_t = \gamma_t y_{t-1}$ where γ_t is a nonnegative random variable with cumulative distribution function Γ , i.e., $\Pr(\gamma_t \leq \gamma) = \Gamma(\gamma)$, and mean $\bar{\gamma} \in (0, (\beta\delta)^{-1})$. The time t dividend becomes known to all agents at the beginning of period t , and at that time each failed production unit is replaced by a new unit that yields dividend y_t in the initial period and follows the same stochastic process as other active units thereafter (the dividend of the initial set of production units, $y_0 \in \mathbb{R}_{++}$, is given at $t = 0$). In the second subperiod of every period, every agent has access to a linear production technology that transforms effort into a perishable homogeneous consumption good.

For each active production unit, there is a durable and perfectly divisible equity share that represents the bearer's ownership of the production unit and confers him the right to

collect dividends. At the beginning of every period $t \geq 1$, each investor receives an endowment of $(1 - \delta) A^s$ equity shares corresponding to the new production units. (When a production unit fails, its equity share disappears.) There is a second financial instrument, money, that is intrinsically useless (it is not an argument of any utility or production function, and unlike equity, ownership of money does not constitute a right to collect any resources). The stock of money at time t is denoted A_t^m . The initial stock of money, $A_0^m \in \mathbb{R}_{++}$, is given and $A_{t+1}^m = \mu A_t^m$, with $\mu \in \mathbb{R}_{++}$. A monetary authority injects or withdraws money via lump-sum transfers or taxes to investors in the second subperiod of every period. At the beginning of period $t = 0$, each investor is endowed with a portfolio of equity shares and money. All financial instruments are perfectly recognizable, cannot be forged, and can be traded in every subperiod.

In the second subperiod of every period, all agents can trade the consumption good produced in that subperiod, equity shares, and money in a spot Walrasian market. In the first subperiod of every period, trading is organized as follows. Investors can trade equity shares and money in a random bilateral *OTC market* with dealers, while dealers can also trade equity shares and money with other dealers in a spot Walrasian *interdealer market*. We use $\alpha \in [0, 1]$ to denote the probability that an individual investor is able to make contact with a dealer in the OTC market. (The probability that a dealer contacts an investor is also α .) Once a dealer and an investor have contacted each other, the pair negotiates the quantity of equity shares and money that the dealer will trade in the interdealer market on behalf of the investor and a fee for the dealer's intermediation services. We assume the terms of the trade between an investor and a dealer in the OTC market are determined by Nash bargaining where $\theta \in [0, 1]$ is the investor's bargaining power. The timing is that the round of OTC trade takes place in the first subperiod and ends before production units yield dividends. Hence equity is traded *cum dividend* in the OTC market (and in the interdealer market) of the first subperiod and *ex dividend* in the Walrasian market of the second subperiod.¹ Asset purchases in the OTC market cannot be financed by borrowing (e.g., due to anonymity and lack of commitment and enforcement). This assumption and the structure of preferences described below create the need for a medium of exchange in the OTC market.

¹As in previous search models of OTC markets, e.g., see Duffie et al. (2005) and Lagos and Rocheteau (2009), an investor must own the equity share in order to consume the dividend.

An individual dealer's preferences are represented by

$$\mathbb{E}_0^d \sum_{t=0}^{\infty} \beta^t (c_{dt} - h_{dt}),$$

where c_{dt} is his consumption of the homogeneous good that is produced, traded, and consumed in the second subperiod of period t , and h_{dt} is the utility cost from exerting h_{dt} units of effort to produce this good. The expectation operator \mathbb{E}_0^d is with respect to the probability measure induced by the dividend process and the random trading process in the OTC market. Dealers get no utility from the dividend good.² An individual investor's preferences are represented by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t (\varepsilon_{it} y_{it} + c_{it} - h_{it}),$$

where y_{it} is the quantity of the dividend good that investor i consumes at the end of the first subperiod of period t , c_{it} is his consumption of the homogeneous good that is produced, traded, and consumed in the second subperiod of period t , and h_{it} is the utility cost from exerting h_{it} units of effort to produce this good. The variable ε_{it} denotes the realization of a valuation shock that is distributed independently over time and across agents, with a differentiable cumulative distribution function G on the support $[\varepsilon_L, \varepsilon_H] \subseteq [0, \infty]$, and $\bar{\varepsilon} = \int \varepsilon dG(\varepsilon)$. Investor i learns his realization ε_{it} at the beginning of period t , before the OTC trading round. The expectation operator \mathbb{E}_0 is with respect to the probability measure induced by the dividend process, the investor's valuation shock, and the random trading process in the OTC market.³

Consider a social planner who wishes to maximize the sum of all agents' expected discounted utilities subject to the same meeting frictions that agents face in the decentralized formulation. Specifically, in the first subperiod of every period, the planner can only reallocate assets among all dealers and the measure α of investors who contact dealers at random. In Appendix C (Proposition 11 in Section C.1), we prove the allocation that solves the planner's problem is characterized by the following two properties: (a) only dealers carry equity between periods, and (b) dealers do not carry assets after the OTC round of trade, and among those investors

²This assumption implies that dealers have no direct consumption motive for holding the equity share. It is easy to relax, but we adopt it because it is the standard benchmark in the search-based OTC literature, e.g., see Duffie et al. (2005), Lagos and Rocheteau (2009), Lagos, Rocheteau, and Weill (2011), and Weill (2007).

³The valuation shock stands in for the various idiosyncratic reasons why individual investors may wish to hold different quantities of a certain asset at different points in time, such as differences in their liquidity needs, financing or financial-distress costs, or hedging needs (e.g., correlation of asset returns with endowments). Several papers that build on the work of Duffie et al. (2005) have formalized the "hedging needs" interpretation. Examples include Duffie et al. (2007), Gârleanu (2009), and Vayanos and Weill (2008).

who have a trading opportunity with a dealer in the OTC market, only those with the highest valuation hold equity shares at the end of the first subperiod. The planner's problem is useful to highlight the two (re)allocation motives that will drive equilibrium outcomes in the following section.⁴ First, the planner implements an efficient allocation of assets in the OTC trading round: Since an investor's utility from the dividend good is linear, and dealers get no utility from the dividend good, the efficient allocation requires that all the assets held by dealers at the beginning of the period are reallocated to the set of investors with the highest valuation for the dividend. Second, by allocating all assets to dealers at the end of every period, the planner ensures that all assets can be reallocated to the set of highest valuation investors in the following OTC trading round with probability one (notice that if instead a set of investors were to enter the OTC round holding the asset, most of these investors would draw valuation shocks strictly lower than ε_H , and the planner would only be able to reallocate a fraction $\alpha < 1$ of those assets to the highest valuation investors who contacted dealers).

3 Equilibrium

Consider the determination of the terms of trade in a bilateral meeting in the OTC round of period t between a dealer with portfolio \mathbf{a}_{dt} and an investor with portfolio \mathbf{a}_{it} and valuation ε . Let $\bar{\mathbf{a}}_t = (\bar{a}_t^m, \bar{a}_t^s)$ denote the investor's post-trade portfolio and let k_t denote the fee the dealer charges for his intermediation services. The fee is expressed in terms of the second-subperiod consumption good and paid by the investor in the second subperiod.⁵ We assume $(\bar{\mathbf{a}}_t, k_t)$ is determined by the Nash bargaining solution where the investor has bargaining power $\theta \in [0, 1]$. Let $\hat{W}_t^D(\mathbf{a}_{dt}, k_t)$ denote the maximum expected discounted payoff of a dealer with portfolio \mathbf{a}_{dt} and earned fee k_t when he reallocates his portfolio in the interdealer market of period t . Let $W_t^I(\mathbf{a}_{it}, k_t)$ denote the maximum expected discounted payoff at the beginning of the second subperiod of period t (after the production units have borne dividends) of an investor who is holding portfolio \mathbf{a}_{it} and has to pay a fee k_t . For each t , define a pair of functions $\bar{a}_t^k : \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H] \rightarrow \mathbb{R}_+$ for $k = m, s$ and a function $k_t : \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H] \rightarrow \mathbb{R}$, and let $\bar{\mathbf{a}}_t(\mathbf{a}_{it}, \varepsilon) = (\bar{a}_t^m(\mathbf{a}_{it}, \varepsilon), \bar{a}_t^s(\mathbf{a}_{it}, \varepsilon))$

⁴Below we show that, under the Friedman rule, the decentralized monetary equilibrium implements the planner's allocation (see Corollary 1).

⁵In the working paper version of this model (Lagos and Zhang, 2015), we instead assume that the investor must pay the intermediation fee on the spot, i.e., with money or equity. The alternative formulation we use here makes the analysis and the exposition much simpler while the main economic mechanisms are essentially unchanged.

for each $(\mathbf{a}_{it}, \varepsilon) \in \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H]$. We use $[\bar{\mathbf{a}}_t(\mathbf{a}_{it}, \varepsilon), k_t(\mathbf{a}_{it}, \varepsilon)]$ to represent the bargaining outcome for a bilateral meeting at time t between an investor with portfolio \mathbf{a}_{it} and valuation ε , and a dealer with portfolio \mathbf{a}_{dt} . That is, $[\bar{\mathbf{a}}_t(\mathbf{a}_{it}, \varepsilon), k_t(\mathbf{a}_{it}, \varepsilon)]$ solves

$$\begin{aligned} \max_{(\bar{\mathbf{a}}_t, k_t) \in \mathbb{R}_+^2 \times \mathbb{R}} & \left[\varepsilon y_t \bar{a}_t^s + W_t^I(\bar{\mathbf{a}}_t, k_t) - \varepsilon y_t a_{it}^s - W_t^I(\mathbf{a}_{it}, 0) \right]^\theta [\hat{W}_t^D(\mathbf{a}_{dt}, k_t) - \hat{W}_t^D(\mathbf{a}_{dt}, 0)]^{1-\theta} \quad (1) \\ \text{s.t.} & \bar{a}_t^m + p_t \bar{a}_t^s \leq a_{it}^m + p_t a_{it}^s \\ & \hat{W}_t^D(\mathbf{a}_{dt}, 0) \leq \hat{W}_t^D(\mathbf{a}_{dt}, k_t) \\ & \varepsilon y_t a_{it}^s + W_t^I(\mathbf{a}_{it}, 0) \leq \varepsilon y_t \bar{a}_t^s + W_t^I(\bar{\mathbf{a}}_t, k_t), \end{aligned}$$

where p_t is the dollar price of an equity share in the interdealer market of period t .

Let $W_t^D(\mathbf{a}_t, k_t)$ denote the maximum expected discounted payoff of a dealer who has earned fee k_t in the OTC round of period t and, at the beginning of the second subperiod of period t , is holding portfolio \mathbf{a}_t . Then the dealer's value of trading in the interdealer market is

$$\begin{aligned} \hat{W}_t^D(\mathbf{a}_t, k_t) &= \max_{\hat{\mathbf{a}}_t \in \mathbb{R}_+^2} W_t^D(\hat{\mathbf{a}}_t, k_t) \quad (2) \\ \text{s.t.} & \hat{a}_t^m + p_t \hat{a}_t^s \leq a_t^m + p_t a_t^s, \end{aligned}$$

where $\hat{\mathbf{a}}_t \equiv (\hat{a}_t^m, \hat{a}_t^s)$. For each t , define a pair of functions, $\hat{a}_t^k : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$ for $k = m, s$, and let $\hat{\mathbf{a}}_t(\mathbf{a}_t) = (\hat{a}_t^m(\mathbf{a}_t), \hat{a}_t^s(\mathbf{a}_t))$ denote the solution to (2).

Let $V_t^D(\mathbf{a}_t)$ denote the maximum expected discounted payoff of a dealer who enters the OTC round of period t with portfolio $\mathbf{a}_t \equiv (a_t^m, a_t^s)$. Let $\boldsymbol{\phi}_t \equiv (\phi_t^m, \phi_t^s)$, where ϕ_t^m is the real price of money and ϕ_t^s the real *ex dividend* price of equity in the second subperiod of period t (both expressed in terms of the second subperiod consumption good). Then,

$$\begin{aligned} W_t^D(\mathbf{a}_t, k_t) &= \max_{(c_t, h_t, \tilde{\mathbf{a}}_{t+1}) \in \mathbb{R}_+^4} [c_t - h_t + \beta \mathbb{E}_t V_{t+1}^D(\mathbf{a}_{t+1})] \quad (3) \\ \text{s.t.} & c_t + \boldsymbol{\phi}_t \tilde{\mathbf{a}}_{t+1} \leq h_t + k_t + \boldsymbol{\phi}_t \mathbf{a}_t, \end{aligned}$$

where $\tilde{\mathbf{a}}_{t+1} \equiv (\tilde{a}_{t+1}^m, \tilde{a}_{t+1}^s)$, $\mathbf{a}_{t+1} = (\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s)$, \mathbb{E}_t is the conditional expectation over the next-period realization of the dividend, and $\boldsymbol{\phi}_t \mathbf{a}_t$ denotes the dot product of $\boldsymbol{\phi}_t$ and \mathbf{a}_t . Similarly, let $V_t^I(\mathbf{a}_t, \varepsilon)$ denote the maximum expected discounted payoff of an investor with valuation ε and portfolio $\mathbf{a}_t \equiv (a_t^m, a_t^s)$ at the beginning of the OTC round of period t . Then,

$$\begin{aligned} W_t^I(\mathbf{a}_t, k_t) &= \max_{(c_t, h_t, \tilde{\mathbf{a}}_{t+1}) \in \mathbb{R}_+^4} \left[c_t - h_t + \beta \mathbb{E}_t \int V_{t+1}^I(\mathbf{a}_{t+1}, \varepsilon') dG(\varepsilon') \right] \quad (4) \\ \text{s.t.} & c_t + \boldsymbol{\phi}_t \tilde{\mathbf{a}}_{t+1} \leq h_t - k_t + \boldsymbol{\phi}_t \mathbf{a}_t + T_t, \end{aligned}$$

where $\mathbf{a}_{t+1} = (\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s + (1 - \delta) A^s)$ and $T_t \in \mathbb{R}$ is the real value of the time t lump-sum monetary transfer.

The value function of an investor who enters the OTC round of period t with portfolio \mathbf{a}_t and valuation ε is

$$V_t^I(\mathbf{a}_t, \varepsilon) = \alpha \{ \varepsilon y_t \bar{a}_t^s(\mathbf{a}_t, \varepsilon) + W_t^I[\bar{\mathbf{a}}_t(\mathbf{a}_t, \varepsilon), k_t(\mathbf{a}_t, \varepsilon)] \} + (1 - \alpha) [\varepsilon y_t a_t^s + W_t^I(\mathbf{a}_t, 0)].$$

The value function of a dealer who enters the OTC round of period t with portfolio \mathbf{a}_t is

$$V_t^D(\mathbf{a}_t) = \alpha \int \hat{W}_t^D[\mathbf{a}_t, k_t(\mathbf{a}_{it}, \varepsilon)] dH_{It}(\mathbf{a}_{it}, \varepsilon) + (1 - \alpha) \hat{W}_t^D(\mathbf{a}_t, 0),$$

where H_{It} is the joint cumulative distribution function over the portfolios and valuations of the investors the dealer may contact in the OTC market of period t .

Let $j \in \{D, I\}$ denote the agent type, i.e., “ D ” for dealers and “ I ” for investors. Then for $j \in \{D, I\}$, let A_{jt}^m and A_{jt}^s denote the quantities of money and equity shares, respectively, held by all agents of type j at the beginning of the OTC round of period t (after production units have depreciated and been replaced). That is, $A_{jt}^m = \int a_t^m dF_{jt}(\mathbf{a}_t)$ and $A_{jt}^s = \int a_t^s dF_{jt}(\mathbf{a}_t)$, where F_{jt} is the cumulative distribution function over portfolios $\mathbf{a}_t = (a_t^m, a_t^s)$ held by agents of type j at the beginning of the OTC round of period t . Let \tilde{A}_{jt+1}^m and \tilde{A}_{jt+1}^s denote the total quantities of money and shares held by all agents of type j at the end of period t , i.e., $\tilde{A}_{Dt+1}^k = \int_{\mathcal{D}} \tilde{a}_{jt+1}^k dj$ and $\tilde{A}_{It+1}^k = \int_{\mathcal{I}} \tilde{a}_{it+1}^k di$ for $k \in \{s, m\}$, with $A_{Dt+1}^m = \tilde{A}_{Dt+1}^m$, $A_{Dt+1}^s = \delta \tilde{A}_{Dt+1}^s$, $A_{It+1}^m = \tilde{A}_{It+1}^m$, and $A_{It+1}^s = \delta \tilde{A}_{It+1}^s + (1 - \delta) A^s$. Let \bar{A}_{Dt}^m and \bar{A}_{Dt}^s denote the quantities of money and shares held after the OTC round of trade of period t by all the dealers, and let \bar{A}_{It}^m and \bar{A}_{It}^s denote the quantities of money and shares held after the OTC round of trade of period t by all the investors who are able to trade in the first subperiod. For asset $k \in \{s, m\}$, $\bar{A}_{Dt}^k = \int \hat{a}_t^k(\mathbf{a}_t) dF_{Dt}(\mathbf{a}_t)$ and $\bar{A}_{It}^k = \alpha \int \bar{a}_t^k(\mathbf{a}_t, \varepsilon) dH_{It}(\mathbf{a}_t, \varepsilon)$. We are now ready to define an equilibrium.

Definition 1 *An equilibrium is a sequence of prices, $\{1/p_t, \phi_t^m, \phi_t^s\}_{t=0}^\infty$, bilateral terms of trade in the OTC market, $\{\bar{\mathbf{a}}_t, k_t\}_{t=0}^\infty$, dealer portfolios, $\{\langle \hat{\mathbf{a}}_{dt}, \tilde{\mathbf{a}}_{dt+1}, \mathbf{a}_{dt+1} \rangle_{d \in \mathcal{D}}\}_{t=0}^\infty$, and investor portfolios, $\{\langle \tilde{\mathbf{a}}_{it+1}, \mathbf{a}_{it+1} \rangle_{i \in \mathcal{I}}\}_{t=0}^\infty$, such that for all t : (i) the bilateral terms of trade $\{\bar{\mathbf{a}}_t, k_t\}_{t=0}^\infty$ solve (1), (ii) taking prices and the bargaining protocol as given, the portfolios $\langle \hat{\mathbf{a}}_{dt}, \tilde{\mathbf{a}}_{dt+1}, \mathbf{a}_{dt+1} \rangle$ solve the individual dealer’s optimization problems (2) and (3), and the portfolios $\langle \tilde{\mathbf{a}}_{it+1}, \mathbf{a}_{it+1} \rangle$ solve the individual investor’s optimization problem (4), and (iii) prices, $\{1/p_t, \phi_t^m, \phi_t^s\}_{t=0}^\infty$, are such that all Walrasian markets clear, i.e., $\tilde{A}_{Dt+1}^s + \tilde{A}_{It+1}^s = A^s$ (the end-of-period t Walrasian market for equity clears), $\tilde{A}_{Dt+1}^m + \tilde{A}_{It+1}^m = A_{t+1}^m$ (the end-of-period t Walrasian market for money*

clears), and $\bar{A}_{Dt}^k + \bar{A}_{It}^k = A_{Dt}^k + \alpha A_{It}^k$ for $k = s, m$ (the period t OTC interdealer markets for equity and money clear). An equilibrium is “monetary” if $\phi_t^m > 0$ for all t and “nonmonetary” otherwise.

The following result characterizes the equilibrium post-trade portfolios of dealers and investors in the OTC market, taking beginning-of-period portfolios as given.

Lemma 1 Define $\varepsilon_t^* \equiv \frac{p_t \phi_t^m - \phi_t^s}{y_t}$ and

$$\chi(\varepsilon_t^*, \varepsilon) \begin{cases} = 1 & \text{if } \varepsilon_t^* < \varepsilon \\ \in [0, 1] & \text{if } \varepsilon_t^* = \varepsilon \\ = 0 & \text{if } \varepsilon < \varepsilon_t^*. \end{cases}$$

Consider a bilateral meeting in the OTC round of period t between a dealer and an investor with portfolio \mathbf{a}_t and valuation ε . The investor’s post-trade portfolio, $[\bar{a}_t^m(\mathbf{a}_t, \varepsilon), \bar{a}_t^s(\mathbf{a}_t, \varepsilon)]$, is given by

$$\begin{aligned} \bar{a}_t^m(\mathbf{a}_t, \varepsilon) &= [1 - \chi(\varepsilon_t^*, \varepsilon)](a_t^m + p_t a_t^s) \\ \bar{a}_t^s(\mathbf{a}_t, \varepsilon) &= \chi(\varepsilon_t^*, \varepsilon)(1/p_t)(a_t^m + p_t a_t^s), \end{aligned}$$

and the intermediation fee charged by the dealer is

$$k_t(\mathbf{a}_t, \varepsilon) = (1 - \theta)(\varepsilon - \varepsilon_t^*) \left[\chi(\varepsilon_t^*, \varepsilon) \frac{1}{p_t} a_t^m - [1 - \chi(\varepsilon_t^*, \varepsilon)] a_t^s \right] y_t.$$

A dealer who enters the OTC market with portfolio \mathbf{a}_{dt} exits the OTC market with portfolio $[\hat{a}_{dt}^m(\mathbf{a}_{dt}), \hat{a}_{dt}^s(\mathbf{a}_{dt})] = [\bar{a}_{dt}^m(\mathbf{a}_{dt}, 0), \bar{a}_{dt}^s(\mathbf{a}_{dt}, 0)]$.

Lemma 1 offers a full characterization of the post-trade portfolios of investors and dealers in the OTC market. First, the bargaining outcome depends on whether the investor’s valuation, ε , is above or below a cutoff, ε_t^* . If $\varepsilon_t^* < \varepsilon$, the investor uses all his cash to buy equity. If $\varepsilon < \varepsilon_t^*$, he sells all his equity holding for cash. The intermediation fee earned by the dealer is equal to a share $1 - \theta$ of the investor’s gain from trade. The dealer’s post-trade portfolio is the same as that of an investor with $\varepsilon = 0$.

We focus the analysis on recursive equilibria, that is, equilibria in which aggregate equity holdings are constant over time, i.e., $A_{Dt}^s = A_D^s$ and $A_{It}^s = A_I^s$ for all t , and real asset prices are time-invariant linear functions of the aggregate dividend, i.e., $\phi_t^s = \phi^s y_t$, $p_t \phi_t^m \equiv \bar{\phi}_t^s = \bar{\phi}^s y_t$, $\phi_t^m A_{It}^m = Z y_t$, and $\phi_t^m A_{Dt}^m = Z_D y_t$, where $Z, Z_D \in \mathbb{R}_+$. Hence, in a recursive equilibrium,

$\varepsilon_t^* = \bar{\phi}^s - \phi^s \equiv \varepsilon^*$, $\phi_{t+1}^s / \phi_t^s = \bar{\phi}_{t+1}^s / \bar{\phi}_t^s = \gamma_{t+1}$, $\phi_t^m / \phi_{t+1}^m = \mu / \gamma_{t+1}$, and $p_{t+1} / p_t = \mu$. Throughout the analysis, we let $\bar{\beta} \equiv \beta\bar{\gamma}$ and maintain the assumption $\mu > \bar{\beta}$ (but we consider the limiting case $\mu \rightarrow \bar{\beta}$).

For the analysis that follows, it is convenient to define

$$\hat{\mu} \equiv \bar{\beta} \left[1 + \frac{(1 - \alpha\theta)(1 - \bar{\beta}\delta)(\hat{\varepsilon} - \bar{\varepsilon})}{\hat{\varepsilon}} \right] \quad \text{and} \quad \bar{\mu} \equiv \bar{\beta} \left[1 + \frac{\alpha\theta(1 - \bar{\beta}\delta)(\bar{\varepsilon} - \varepsilon_L)}{\bar{\beta}\delta\bar{\varepsilon} + (1 - \bar{\beta}\delta)\varepsilon_L} \right], \quad (5)$$

where $\hat{\varepsilon} \in [\bar{\varepsilon}, \varepsilon_H]$ is the unique solution to

$$\bar{\varepsilon} - \hat{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\hat{\varepsilon}} (\hat{\varepsilon} - \varepsilon) dG(\varepsilon) = 0. \quad (6)$$

Lemma 4 (in Appendix A) establishes that $\hat{\mu} < \bar{\mu}$. The following proposition characterizes the equilibrium set.

Proposition 1 (i) A nonmonetary equilibrium exists for any parametrization. (ii) There is no recursive monetary equilibrium if $\mu \geq \bar{\mu}$. (iii) In the nonmonetary equilibrium, $A_I^s = A^s - A_D^s = A^s$ (only investors hold equity shares), there is no trade in the OTC market, and the equity price in the second subperiod is

$$\phi_t^s = \phi^s y_t, \quad \text{with} \quad \phi^s = \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \bar{\varepsilon}. \quad (7)$$

(iv) If $\mu \in (\bar{\beta}, \bar{\mu})$, then there is one recursive monetary equilibrium; asset holdings of dealers and investors at the beginning of the OTC round of period t are $A_{D_t}^m = A_t^m - A_{I_t}^m = 0$ and

$$A_D^s = A^s - A_I^s \begin{cases} = \delta A^s & \text{if } \bar{\beta} < \mu < \hat{\mu} \\ \in [0, \delta A^s] & \text{if } \mu = \hat{\mu} \\ = 0 & \text{if } \hat{\mu} < \mu < \bar{\mu} \end{cases}$$

and asset prices are

$$\phi_t^s = \phi^s y_t, \quad \text{with} \quad \phi^s = \begin{cases} \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \varepsilon^* & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] & \text{if } \hat{\mu} < \mu < \bar{\mu} \end{cases} \quad (8)$$

$$\bar{\phi}_t^s = \bar{\phi}^s y_t, \quad \text{with} \quad \bar{\phi}^s = \varepsilon^* + \phi^s \quad (9)$$

$$\phi_t^m = Z \frac{y_t}{A_t^m} \quad (10)$$

$$p_t = \frac{\bar{\phi}^s}{Z} A_t^m, \quad (11)$$

where

$$Z = \frac{\alpha G(\varepsilon^*) A_I^s + A_D^s}{\alpha [1 - G(\varepsilon^*)]} (\varepsilon^* + \phi^s) \quad (12)$$

and for any $\mu \in (\bar{\beta}, \bar{\mu})$, $\varepsilon^* \in (\varepsilon_L, \varepsilon_H)$ is the unique solution to

$$\frac{(1 - \bar{\beta}\delta) \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon)}{\varepsilon^* + \bar{\beta}\delta \left[\bar{\varepsilon} - \varepsilon^* + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] \mathbb{I}_{\{\bar{\mu} < \mu\}}} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} = 0. \quad (13)$$

(v) (a) As $\mu \rightarrow \bar{\mu}$, $\varepsilon^* \rightarrow \varepsilon_L$ and $\phi_t^s \rightarrow \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \bar{\varepsilon} y_t$. (b) As $\mu \rightarrow \bar{\beta}$, $\varepsilon^* \rightarrow \varepsilon_H$ and $\phi_t^s \rightarrow \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \varepsilon_H y_t$.

In the nonmonetary equilibrium, dealers are inactive and equity shares are held only by investors. With no valued money, investors and dealers cannot exploit the gains from trade that arise from the heterogeneity in investor valuations in the first subperiod, and the real asset price is $\phi^s = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \bar{\varepsilon} y$, i.e., equal to the expected discounted value of the dividend stream since the equity share is not traded. (Shares can be traded in the Walrasian market of the second subperiod, but gains from trade at that stage are nil.) The recursive monetary equilibrium exists only if the inflation rate is not too high, i.e., if $\mu < \bar{\mu}$. In the monetary equilibrium, the marginal valuation, ε^* , which according to Lemma 1 partitions the set of investors into those who buy and those who sell the asset when they meet a dealer in the OTC market, is characterized by (13) in part (iv) of Proposition 1. Unlike what happens in the nonmonetary equilibrium, the OTC market is active in the monetary equilibrium, and it is easy to show that the marginal valuation, ε^* , is strictly decreasing in the rate of inflation, i.e., $\frac{\partial \varepsilon^*}{\partial \mu} < 0$ (see Corollary 3 in Appendix A). Intuitively, the real value of money falls as μ increases, so the marginal investor valuation, ε^* , decreases, reflecting the fact that under the higher inflation rate, the investor that was marginal under the lower inflation rate is no longer indifferent between carrying cash and equity out of the OTC market—he prefers equity.

According to Proposition 1, $0 \leq \varepsilon_L < \varepsilon_t^*$ in the monetary equilibrium, so Lemma 1 implies that dealers hold no equity shares at the end of the OTC round: all equity is held by investors, in particular, by those investors who carried equity into the period but were unable to contact a dealer, and by those investors who purchased equity shares in bilateral trades with dealers. After the round of OTC trade, all the money supply is held by the investors who carried cash into the period but were unable to contact a dealer, by the investors who sold equity shares through dealers, and by those dealers who carried equity into the OTC market.

A feature of the monetary equilibrium is that dealers never hold money overnight: at the beginning of every period t , the money supply is all in the hands of investors, i.e., $A_{Dt}^m = 0$ and

$A_{I_t}^m = A_t^m$. The reason is that access to the interdealer market allows dealers to intermediate assets without cash. Whether it is investors or dealers who hold the equity shares overnight depends on the inflation rate: if it is low, i.e., if $\mu \in (\bar{\beta}, \hat{\mu})$, then only dealers hold equity overnight, that is, $\tilde{A}_{D_{t+1}}^s = A^s$ and $\tilde{A}_{I_{t+1}}^s = 0$ for all t . Conversely, if the inflation rate is high, i.e., if $\mu \in (\hat{\mu}, \bar{\mu})$, then at the end of every period t , all equity shares are in the hands of investors, i.e., $\tilde{A}_{D_{t+1}}^s = 0$ and $\tilde{A}_{I_{t+1}}^s = A^s$, so strictly speaking, in this case dealers only provide brokerage services in the OTC market. The intuition for this result is as follows.⁶ For dealers, the return from holding equity overnight is given by the resale price in the OTC market. If inflation is low, ε_t^* is high (the asset is priced by relatively high valuation investors), and this means the resale price in the OTC market is high. Since dealers are sure to trade in the OTC market every period while investors only trade with effective probability $\alpha\theta$, the former are in a better position to reap the capital gains and end up holding all equity shares overnight. Conversely, if inflation is high then ε_t^* is low, so the capital gain to a dealer from carrying the asset to sell in the OTC market is small. The benefit to investors from holding equity includes not only the resale value in the OTC market (which is small at high inflation) but also their own expected valuation of the dividend good, so for high inflation, the return that investors obtain from holding equity overnight is higher than it is for dealers. For example, as $\mu \rightarrow \bar{\mu}$ we have $\varepsilon_t^* \rightarrow \varepsilon_L$, so the dealer's expected return from holding equity overnight is $\frac{(\varepsilon_L + \phi^s)\bar{\gamma}}{\phi^s}$, while the investor's is $\frac{(\bar{\varepsilon} + \phi^s)\bar{\gamma}}{\phi^s}$.

Given the marginal valuation, ε^* , part (iv) of Proposition 1 gives all asset prices in closed form. The real ex dividend price of equity (in terms of the second subperiod consumption good), ϕ_t^s , is given by (8). The cum dividend dollar price of equity in the OTC market, p_t , is given by (11). The real price of money (in terms of the second subperiod consumption good), ϕ_t^m , is given by (10). The real cum dividend price of equity (in terms of the second subperiod consumption good) in the OTC market, $p_t \phi_t^m = \bar{\phi}^s y_t$, is given by (9).

Finally, part (v)(a) states that as the rate of money creation increases toward $\bar{\mu}$, ε^* approaches the lower bound of the distribution of valuations, ε_L , so no investor wishes to sell equity in the OTC market, and as a result the allocations and prices of the monetary equilibrium approach those of the nonmonetary equilibrium. Part (v)(b) states that as μ decreases toward $\bar{\beta}$, ε^* increases toward the upper bound of the distribution of valuations, ε_H , so only investors with the highest valuation purchase equity in the OTC market (all other investors

⁶See Lagos and Zhang (2015) for a more detailed discussion.

wish to sell it). Moreover, since $\bar{\beta} < \hat{\mu}$, as $\mu \rightarrow \bar{\beta}$ only dealers hold equity overnight. Thus, we have the following result.

Corollary 1 *The allocation implemented by the recursive monetary equilibrium converges to the efficient allocation as $\mu \rightarrow \bar{\beta}$.*

Let $q_{t,k}^B$ denote the nominal price in the second subperiod of period t of an N -period risk-free pure discount nominal bond that matures in period $t+k$, for $k = 0, 1, 2, \dots, N$ (so k is the number of periods until the bond matures). Imagine the bond cannot be used as means of payment in the first subperiod.⁷ Then in a recursive monetary equilibrium, $q_{t,k}^B = (\bar{\beta}/\mu)^k$, and $i = \mu/\bar{\beta} - 1$ is the time t nominal yield to maturity of the bond with k periods until maturity. Thus, the optimal monetary policy described in Corollary 1 and part (v)(b) of Proposition 1 in which $\mu = \bar{\beta}$ can be interpreted as a policy that implements the *Friedman rule*, i.e., $i = 0$ for all contingencies at all dates. Since the (gross) inflation rate is $\phi_t^m/\phi_{t+1}^m = \mu \frac{y_t}{y_{t+1}} \equiv 1 + \pi_{t+1}$, $1 + i = \mu/\bar{\beta}$ is equivalent to

$$1 + i = (1 + r)(1 + \pi), \quad (14)$$

with $1 + \pi \equiv \left[\mathbb{E}_t \frac{1}{1 + \pi_{t+1}} \right]^{-1} = \mu/\bar{\gamma}$.

4 Implications

In this section, we discuss the main implications of the theory. Specifically, we show how asset prices and trade volume are determined by monetary policy and the details of the microstructure where the asset trades (e.g., the degree of market power of dealers and the ease with which investors find counterparties).⁸

⁷Notice that even though the bond cannot be traded for equity in the OTC round of trade, it can be exchanged (or redeemed) for money at the end of the period at no cost. Hence how “illiquid” we deem this bond depends on the length of the model period. If, as in the quantitative analysis of Section 6, the model period corresponds to one trading day, then the bond is in fact very liquid, or “very close to cash” according to the usual real-world standards.

⁸We focus on trade volume as a measure of financial liquidity because it will be the relevant variable in our empirical analysis. For completeness, in Appendix A (Section A.5) we show how conventional measures of financial liquidity other than trade volume (e.g., spreads, and dealer supply of immediacy) are determined by monetary policy and the details of the microstructure. In Appendix A (Section A.7) we also show that generically, asset prices in the monetary economy exhibit a speculative premium whose size varies systematically with monetary policy and the market microstructure.

4.1 Asset prices

In this subsection, we study the asset-pricing implications of the theory. We focus on how the asset price depends on monetary policy and on the degree of OTC frictions as captured by the parameters that regulate trading frequency and the relative bargaining strengths of traders.⁹

The real price of equity in a monetary equilibrium is in part determined by the option available to low-valuation investors to resell the equity to high-valuation investors. If the growth rate of the money supply (and therefore the inflation rate) increases, equilibrium real money balances decline and the marginal investor valuation, ε^* , decreases, reflecting the fact that under the higher inflation rate, the investor valuation that was marginal under the lower inflation rate is no longer indifferent between carrying cash and equity out of the OTC market—he prefers equity. Since the marginal investor who prices equity in the OTC market has a lower valuation, the value of the resale option is smaller, i.e., the *turnover liquidity* of the asset is lower, which in turn makes the real equity price (both ϕ^s and $\bar{\phi}^s$) smaller. Naturally, the real value of money, ϕ_t^m , is also decreasing in the growth rate of the money supply.¹⁰ All this is formalized in Proposition 2.

Proposition 2 *In the recursive monetary equilibrium: (i) $\partial\phi^s/\partial\mu < 0$, (ii) $\partial\bar{\phi}^s/\partial\mu < 0$, (iii) $\partial Z/\partial\mu < 0$ and $\partial\phi_t^m/\partial\mu < 0$.*

Proposition 2 is useful for settings where monetary policy operates by changing the expected inflation rate, i.e., settings where changes in i are associated exclusively with changes in π in (14). The following result examines the behavior of real asset prices in settings where changes in i are associated exclusively with changes in the real interest rate, r .¹¹

Proposition 3 *In the recursive monetary equilibrium: (i) $\partial\phi^s/\partial r < 0$, (ii) $\partial Z/\partial r < 0$ and $\partial\phi_t^m/\partial r < 0$.*

⁹In Appendix A (Proposition 9) we also establish the effect of a mean-preserving spread in the distribution of valuations on the equity price.

¹⁰The top row of Figure 8 (Appendix A) illustrates the typical time paths of the ex dividend equity price, ϕ_t^s , real balances, $\phi_t^m A_t^m$, and the price level, ϕ_t^m , for different values of μ .

¹¹The proof of Proposition 3 (Appendix A, Section A.4) is based on a continuous-time version of our discrete-time economy. The continuous-time formulation can be interpreted as an approximation to our baseline discrete-time model when the period length is small. Apart from allowing sharper analytical results, the continuous-time formulation is useful since the model period in our quantitative implementation of the theory is very short (specifically, a trading day; see Section 6.2 for details).

In the OTC market, $\alpha\theta$ is an investor's effective bargaining power in negotiations with dealers. A larger $\alpha\theta$ implies a larger gain from trade for low-valuation investors when they sell the asset to dealers. In turn, this makes investors more willing to hold equity shares in the previous period, since they anticipate larger gains from selling the equity in case they were to draw a relatively low valuation in the following OTC round. Hence, real equity prices, ϕ^s and $\bar{\phi}^s$, are increasing in α and θ .¹² If α increases, money becomes more valuable (both Z and ϕ_t^m increase), provided we focus on a regime in which only investors carry equity overnight.¹³ Proposition 4 formalizes these ideas.

Proposition 4 *In the recursive monetary equilibrium: (i) $\partial\phi^s/\partial(\alpha\theta) > 0$, (ii) $\partial\bar{\phi}^s/\partial(\alpha\theta) > 0$, (iii) $\partial Z/\partial\alpha > 0$ and $\partial\phi_t^m/\partial\alpha > 0$, for $\mu \in (\hat{\mu}, \bar{\mu})$.*

4.2 Trade volume

Trade volume is commonly used as a measure of market liquidity because it is a manifestation of the ability of the market to reallocate assets across investors. According to Lemma 1, any investor with $\varepsilon < \varepsilon_t^*$ who has a trading opportunity in the OTC market sells all his equity holding. Hence, in a recursive equilibrium, the quantity of assets sold by investors to dealers in the OTC market is $Q^s = \alpha G(\varepsilon^*) A_I^s$. From Lemma 1, the quantity of assets purchased by investors from dealers is $Q^b = \alpha [1 - G(\varepsilon^*)] A_t^m/p_t$. Thus, the total quantity of equity shares traded in the OTC market is $\mathcal{V} = Q^b + Q^s$, or equivalently¹⁴

$$\mathcal{V} = 2\alpha G(\varepsilon^*) A_I^s + A_D^s. \quad (15)$$

Trade volume, \mathcal{V} , depends on the growth rate of the money supply, μ , (or equivalently, expected inflation), the real interest rate, r , and dealers' market power θ indirectly, through the general equilibrium effect on ε^* . A decrease in μ or r , or an increase in θ increases the expected return to holding money relative to equity, which makes more investors willing to sell equity for money in the OTC market, i.e., ε^* increases and so does trade volume, provided $G'(\varepsilon^*) > 0$. In other

¹²This finding is consistent with the behavior of the illiquidity premia in response to variations in the measures of liquidity documented by Ang et al. (2013).

¹³Real balances can actually fall with α for $\mu \in (\bar{\beta}, \hat{\mu})$. The bottom row of Figure 8 (Appendix A) illustrates the time paths of the ex dividend equity price, ϕ_t^s , real balances $\phi_t^m A_t^m$, and the price level, ϕ_t^m , for two different values of α .

¹⁴To obtain (15) we used the clearing condition for the interdealer market, $Q^b = Q^s + A_{Dt}^s$. Also, note that \mathcal{V} is trade volume in the OTC market, but since every equity share traded in the first subperiod gets retraded in the second subperiod, total trade volume in the whole time period equals $2\mathcal{V}$.

words, the increase in *turnover liquidity* caused by a decrease in μ or r , or an increase in θ will manifest itself through an increase in trade volume provided the cumulative distribution of investors is strictly increasing over the relevant range. The indirect positive effect on \mathcal{V} (through ε^*) of an increase in the investors' trade probability α is similar to an increase in θ , but in addition, α directly increases trade volume, since with a higher α more investors are able to trade in the OTC market. These results are summarized in the following proposition.

Proposition 5 *In the recursive monetary equilibrium, provided provided $G'(\varepsilon^*) > 0$: (i) $\partial\mathcal{V}/\partial\mu < 0$, (ii) $\partial\mathcal{V}/\partial r < 0$, (iii) $\partial\mathcal{V}/\partial\theta > 0$ and $\partial\mathcal{V}/\partial\alpha > 0$.*

4.3 Discussion

In this section we explain the economic rationale behind Propositions 2 and 3. To streamline the exposition, focus on a recursive monetary equilibrium in which investors carry equity overnight. In this case, the Euler equations for money and equity are:

$$\phi_t^m = \frac{1}{1+r} \mathbb{E}_t \left[\phi_{t+1}^m + \alpha\theta \int_{\varepsilon^*}^{\varepsilon_H} \frac{(\varepsilon - \varepsilon^*)y_{t+1}}{p_{t+1}} dG(\varepsilon) \right] \quad (16)$$

$$\phi_t^s = \frac{1}{1+r} \delta \mathbb{E}_t \left[\bar{\varepsilon}y_{t+1} + \phi_{t+1}^s + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) y_{t+1} dG(\varepsilon) \right]. \quad (17)$$

(See Corollary 2 in Appendix A for details.) On the left side of (16), ϕ_t^m represents the cost (in terms of the second-subperiod consumption good) of purchasing an additional dollar in the competitive market of the second subperiod of period t . On the right side of (16) is the discounted expected value of the additional dollar in period $t+1$. This marginal value equals the expected value from holding the dollar for a whole period (until the competitive trading round at the end of period $t+1$), i.e., ϕ_{t+1}^m , plus the expected value of the option to exchange the dollar for equity shares in the OTC round at the beginning of period $t+1$. This option is executed provided the investor gets access to the interdealer market (with probability α), gets a share θ of the gain from trade with the dealer, and gets a random valuation higher than ε^* , so the expected gain from exchanging the dollar for equity is $\alpha\theta \int_{\varepsilon^*}^{\varepsilon_H} \frac{(\varepsilon - \varepsilon^*)y_{t+1}}{p_{t+1}} dG(\varepsilon)$. Next, consider (17). On the left side, ϕ_t^s represents the cost (in terms of the second-subperiod consumption good) of purchasing an additional equity share in the competitive market of the second subperiod of period t . On the right side is the discounted (net of depreciation) expected value of the additional equity share in period $t+1$. This marginal value equals the expected

cum-dividend value from holding the equity share for a whole period (until the competitive trading round at the end of period $t + 1$), i.e., $\bar{\varepsilon}y_{t+1} + \phi_{t+1}^s$, plus the expected value of the option to resell the asset in the OTC round at the beginning of period $t + 1$. This resale option is executed provided the investor gets access to the interdealer market (with probability α), gets a share θ of the gain from trade with the dealer, and gets a random valuation lower than ε^* , so the expected value of the resale option is $\alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) y_{t+1} dG(\varepsilon)$. This additional term that makes the equilibrium real value of an equity share larger than the discounted expected value of the dividend stream is reminiscent of the value of the resale option in Harrison and Kreps (1978). The novelty here is that the value of this resale option depends on monetary policy—through the effect that monetary policy has on asset reallocation and the determination of the marginal investor valuation, ε^* , in the OTC round.

Given $p_t \phi_t^m \equiv (\varepsilon^* + \phi^s) y_t$, $\phi_t^m / \phi_{t+1}^m = \mu / \gamma_{t+1}$, $\mathbb{E}_t y_{t+1} = \mathbb{E}_t \gamma_{t+1} y_t = \bar{\gamma} y_t$, and (14), the Euler equation (16) can be written as

$$1 = \frac{1}{1+i} \left[1 + \alpha\theta \int_{\varepsilon^*}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^*}{\varepsilon^* + \phi^s} dG(\varepsilon) \right]. \quad (18)$$

The left side is the real cost of purchasing an additional unit of real money balances (1 unit of the numeraire good). The right side is the discounted expected value of bringing an additional unit of real money balances into the OTC round of the following period. Condition (18) makes clear that an increase in the nominal rate, i , acts as a tax on real money balances: it reduces the incentives to carry money, which in turn reduces the valuation of the marginal investor, ε^* . As a result, the real equity price falls, as is clear from (17). Notice that this result holds both, if the increase in the nominal rate is associated with an increase in expected inflation, π , as in part (i) of Proposition 2, and if the increase in the nominal rate is associated with an increase in the real interest rate, r , as in part (i) of Proposition 3. The intuitive reason why ε^* falls in response to an increase in the nominal rate has to do with the fact that while in general equilibrium a change in i affects investors' valuations of both equity and money, it affects the incentive to hold money relatively more.

To understand this, first suppose the increase in i is associated with an increase in expected inflation, π , or equivalently, the money growth rate, μ . The pricing equation (18) indicates that the first-order (partial equilibrium) effect of π is to reduce the real value of a dollar, and that this is achieved by a reduction in ε^* , i.e., a reduction in the equilibrium cum-dividend value of an equity share that money is used to buy. The Euler equation for equity, (17) does not

depend on π directly; only indirectly through the general equilibrium effect of π on real money balances. The direct effect of expected inflation on the real value of money is larger than the indirect effect on the price of equity, and the marginal investor valuation, ε^* , decreases as the investor that was marginal under the lower inflation rate tilts his portfolio away from money toward equity in an attempt to avoid the inflation tax.

For another angle on this logic, suppose the background monetary policy is the Friedman rule, as in Corollary 1. In this case the opportunity cost of holding money is zero, i.e., $i = 0$, so investors are willing to hold enough real money balances to satiate their random demand for liquidity in the OTC round, i.e., (18) implies $\varepsilon^* = \varepsilon_H$ if $i = 0$. Intuitively, this means that the highest valuation investors (those with valuations equal to ε_H) who contact dealers are able to absorb the whole supply of equity shares in the interdealer market, and the equilibrium equity price reflects only their valuation. If the inflation rate is higher than the target level prescribed by the Friedman rule, then the opportunity cost of holding money is positive, and therefore the highest valuation investors are budget constrained in the OTC round as they no longer choose to hold enough real money balances to be financially unconstrained for every realization of the next-period valuation (formally, (18) implies $\varepsilon^* < \varepsilon_H$ if $i > 0$). Since investors with valuation ε_H are no longer able to absorb the whole asset supply traded in the interdealer market, investors with lower valuations are now able to purchase some equity shares, and therefore the marginal investor who prices equity has valuation $\varepsilon^* < \varepsilon_H$. In sum, as π increases, aggregate real balances fall, investors with relatively high valuations become less able to express their valuations, and as a result, the asset is held—and priced—by investors with lower valuations.

To conclude, suppose the increase in i is associated with an increase in the real rate, r . In this case we have shown that ε^* also falls, again reflecting the fact that an increase in the real rate reduces the value of money relatively more than the value of an equity share. The reason is that, since equity dominates money in terms of rate of return (equity yields a real dividend and money does not), an equilibrium with valued money necessarily requires that money be a relatively better store of value than equity (formally, $\mu < \bar{\mu}$). This means that while an increase in r reduces investors' valuations of both equity and money, it has a relatively smaller effect on the incentive to hold equity—which necessarily has a more “front-loaded” payoff structure than money in the monetary equilibrium.

5 Empirical analysis

According to the theory, the real asset price decreases in response to an entirely unanticipated and permanent increase in the nominal interest rate (part (i) of Proposition 2 and part (i) of Proposition 3, together with (14)). The mechanism through which the increase in the nominal rate is transmitted to the asset price is a reduction in *turnover liquidity*, i.e., a reduction in the resale option value, accompanied by a nonpositive change in trade volume (parts (i) and (ii) of Proposition 5). These two theoretical results suggest two hypotheses that can be tested with price and turnover data: (a) surprise increases in the nominal rate reduce the marketwide stock return (and possibly trade volume), and (b) the strength of the mechanism depends on the turnover liquidity of the stocks (e.g., as proxied for by the turnover rate of the stock). The following proposition (based on a generalization of the theory with multiple assets indexed by $s \in \{1, 2, \dots, N\}$ that differ in terms of the trading frequency, α^s) provides a formal theoretical basis for these two hypotheses.

Proposition 6 *In the recursive monetary equilibrium, (i) $\partial \log \phi^s / \partial \pi < 0$, (ii) $\partial \log \phi^s / \partial r < 0$, (iii) $\partial^2 \log \phi^s / (\partial \alpha^s \partial \pi) < 0$, (iv) $\partial^2 \log \phi^s / (\partial \alpha^s \partial r) < 0$.*

Thus, theory predicts a negative semi-elasticity of the real equity price with respect to the nominal interest rate, regardless of whether the increase in the nominal rate is associated with an increase in the expected inflation rate, π , or an increase in the real rate, r (parts (i) and (ii) of Proposition 6). Moreover, since turnover is an increasing function of α^s , theory predicts that the magnitude of this semi-elasticity is larger for stocks with higher turnover (parts (iii) and (iv) of Proposition 6).

5.1 Data

We use daily time series for all individual common stocks in the New York Stock Exchange (NYSE) from the Center for Research in Security Prices (CRSP).¹⁵ The daily stock return from CRSP takes into account changes in prices and accrued dividend payment, i.e., the return of stock s on day t is $\mathcal{R}_t^s = \left(\frac{P_t^s + D_t^s}{P_{t-1}^s} - 1 \right) \times 100$, where P_t^s is the ex dividend dollar price of stock s on day t , and D_t^s denotes the dollar dividend paid per share of stock s on day t . As a measure of trade volume for each stock, we construct the daily *turnover rate* from CRSP, i.e.,

¹⁵We report results for NASDAQ stocks in Appendix D (Section D.3).

$\mathcal{T}_t^s = \mathcal{V}_t^s / A_t^s$, where \mathcal{V}_t^s is the trade volume of stock s on day t (measured as the total number of shares traded) and A_t^s is the number of outstanding shares of stock s on day t . Whenever we use an average, e.g., of equity returns or turnover rates across a set of stocks, we use the arithmetic average, e.g., $\mathcal{R}_t^I = \frac{1}{n} \sum_{s=1}^n \mathcal{R}_t^s$ and $\mathcal{T}_t^I = \frac{1}{n} \sum_{s=1}^n \mathcal{T}_t^s$ are the average return and the average turnover rate for the universe of n common stocks listed in the NYSE.¹⁶

As a proxy for the policy (nominal interest) rate, we use the rate on the nearest Eurodollar futures contract due to mature after the FOMC policy announcement, as in Rigobon and Sack (2004).¹⁷ Specifically, we use the 3-month Eurodollar futures rate produced by the Chicago Mercantile Exchange Group (CME Group) and supplied by Datastream. In some of our empirical estimations, we use the tick-by-tick nominal interest rate implied by 30-day federal funds futures and consider a high-frequency measure of the unexpected change in the nominal policy rate in a narrow 30-minute time window around the FOMC announcement. The sample we analyze runs from January 3, 1994 to December 31, 2007.¹⁸ The sample includes between 1300 and 1800 stocks (depending on the time period) and 133 FOMC announcement dates.¹⁹

¹⁶We report results for value-weighted returns in Appendix D (Section D.4).

¹⁷Eurodollar futures are based on a \$1 million face value 3-month maturity Eurodollar time deposit. These futures contracts mature during the conventional IMM (International Monetary Market) dates in the months of March, June, September, or December, extending outward 10 years into the future. In addition, at any point in time, there are so-called 3-month Eurodollar *serial contracts* extending 4 months into the future that mature in months that are not conventional IMM dates. For example, at the beginning of January 2016, there are contracts maturing in mid-March, mid-June, mid-September, and mid-December of 2016, through 2025. There are also serial contracts maturing in mid-January, mid-February, mid-April, and mid-May of 2016. Thus, depending on the timing of the FOMC announcement, the nearest contract to mature may expire between zero and 30 days after the announcement. Current quotes are available at http://www.cmegroup.com/trading/interest-rates/stir/eurodollar_quotes_settlements_futures.html. An advantage of using a futures rate as a proxy for the “policy rate” is that its movement on dates of FOMC policy announcements reflects policy surprises only and does not reflect anticipated policy changes. The importance of focusing on the surprise component of policy announcements (rather than on the anticipated component) in order to identify the response of asset prices to monetary policy was originally pointed out by Kuttner (2001) and has been emphasized by the literature since then, e.g., Bernanke and Kuttner (2005) and Rigobon and Sack (2004). Gürkaynak et al. (2007) offer empirical evidence supporting the use of futures contracts as an effective proxy for policy expectations and discuss their use to define policy shocks.

¹⁸We start our sample period in 1994 because prior to 1994, policy changes in the federal funds target were unannounced and frequently occurred between FOMC meetings. From 1994 onward, all changes are announced and most coincided with FOMC meetings, so as policy announcement dates we use the dates of FOMC meetings obtained from the website of the Board of Governors of the Federal Reserve System. The web address is <http://www.federalreserve.gov/monetarypolicy/fomccalendars.htm>. See Bernanke and Kuttner (2005) for more discussion on the exact timing of policy announcements.

¹⁹Our full sample contains 135 policy dates. We discard two dates: 9/13/2001 and 9/17/2001 (the two atypical FOMC announcements in the immediate aftermath of 9/11/2001). One of our estimation procedures requires data involving first differences in variables on the policy day and on the day preceding the policy day. In that case, we follow Rigobon and Sack (2004) and discard three additional policy dates because they are preceded by either one or two holidays in financial markets. Another of our estimation procedures relies on high-frequency

In the following subsections, we use the data described above to estimate the sign and magnitude of the effect of monetary policy on stock returns and turnover. In Subsection 5.2, we estimate these effects for FOMC announcement days for a broad index of stocks. In Subsection 5.3, we document that the strength of the effect of monetary policy on stock returns differs systematically with the turnover liquidity of the stock. In Subsection 5.4, we go a step further and estimate the dynamic effects of the policy announcement on returns and turnover.

5.2 Aggregate announcement-day effects

The empirical literature has followed several approaches to estimate the impact of monetary policy on the stock market. A popular one, known as *event-study analysis*, consists of estimating the market reaction to monetary policy surprises on a subsample of trading days consisting exclusively of the days of FOMC announcements (we denote this subsample S_1). Let i_t denote the day t “policy rate” (in our case, the CME Group 3-month Eurodollar future with closest expiration date at or after day t , expressed in percentage terms) and define $\Delta i_t \equiv i_t - i_{t-1}$. The event-study analysis consists of running the following regression:

$$Y_t^I = a + b\Delta i_t + \epsilon_t \quad (19)$$

for $t \in S_1$, with $Y_t^I = \mathcal{R}_t^I$, where ϵ_t is an exogenous shock to the asset price.²⁰ We refer to the estimator b as the *event-study estimator* (or “E-based” estimator, for short).

A concern with (19) is that it does not take into account the fact that the policy rate on the right side may itself be reacting to asset prices (a simultaneity bias) and that a number of other variables (e.g., news about economic outlook) are likely to have an impact on both the policy rate and asset prices (an omitted variables bias). This concern motivates us to also consider two other estimators: the *heteroskedasticity-based estimator* (“H-based” estimator, for short) proposed by Rigobon and Sack (2004), and a version of the event-study estimator that relies on an instrumental variable identification strategy that uses intraday high-frequency tick-by-tick interest rate data. The H-based estimator identifies the response of asset prices

market activity in a narrow time interval around the exact time of the monetary policy announcement. In this case, we use the data from Gorodnichenko and Weber (2016) that consists of 118 scheduled policy dates. For each trading day, we discard observations whose return or turnover rate on that given day is in the top or bottom 1 percentile.

²⁰In the context of monetary policy, this approach was originally used by Cook and Hahn (1989) and has been followed by a large number of papers, e.g., Bernanke and Kuttner (2005), Cochrane and Piazzesi (2002), Kuttner (2001), and Thorbecke (1997).

based on the heteroskedasticity of monetary policy shocks. The *high-frequency instrumental variable estimator* (“HFIV” estimator, for short) addresses the omitted variable bias and the concern that the Eurodollar futures rate may itself respond to market conditions on policy announcement days, by focusing on changes in a proxy for the policy rate in a very narrow 30-minute window around the time of the FOMC announcement.²¹

Table 1 presents the baseline results. The first column corresponds to the event-based estimation, the second column corresponds to the heteroskedasticity-based estimation, and the third column corresponds to the high-frequency instrumental variable estimation. Returns are expressed in percentage terms. The first row presents estimates of the reaction of the marketwide NYSE return to monetary policy. The point estimate for b in (19) is -5.47 . This means that a 1 basis point (bp) increase in the policy rate causes a decrease of 5.47 basis points (bps) in the stock market return on the day of the policy announcement.²² The analogous H-based point estimate is -11.31 . These results are in line with those reported in previous studies.²³ The HFIV point estimate is -9.38 , implying that a 25 bp surprise increase in the policy rate causes a decrease in the stock market return of 2.34 percentage points (pps) on the day of the policy announcement.²⁴ Figure 1 shows a scatterplot with the unexpected change in the policy rate (measure by the high-frequency change in the fed funds future rate) on the horizontal axis, and the announcement-day marketwide stock return on the vertical axis, both expressed in bps. The negative relationship between stock returns and fed funds rate surprises is readily visible from the fitted line.

Previous studies have not clearly identified the specific economic mechanism that transmits monetary policy shocks to the stock market. Conventional asset-pricing theory suggests three broad immediate reasons why an unexpected policy nominal rate increase may lead to a decline in stock prices. It may be associated with a decrease in expected dividend growth, with a rise in the future real interest rates used to discount dividends, or with an increase in the expected

²¹In Appendix B we discuss the derivation of the H-based estimator (Section B.1) and describe the construction of the HFIV estimator (Section B.2).

²²The R^2 indicates that 14 percent of the variance of equity prices in days of FOMC policy announcements is associated with news about monetary policy.

²³The comparable event-based estimates in Bernanke and Kuttner (2005), who focus on a different sample period and measure stock returns using the value-weighted return from CRSP, range between -2.55 and -4.68 . The comparable heteroskedasticity-based estimates in Rigobon and Sack (2004), who use a different series for the Eurodollar forward rate, are -6.81 for the S&P 500 index, -6.5 for the WIL5000 index, -9.42 for the NASDAQ, and -4.85 for the DJIA.

²⁴In comparing the E-based, H-based, and HFIV estimates, one should bear in mind that the number of policy dates varies slightly between the three estimation methods, as explained in footnote 19.

excess returns (i.e., equity premia) associated with holding stocks. Our theory formalizes a new mechanism: the reduction in turnover liquidity caused by the increase in the opportunity cost of holding the nominal assets that are routinely used to settle financial transactions. To begin assessing this mechanism, we again estimate b in (19), and the analogous H-based and HFIV estimates, but with $Y_t^I = \mathcal{T}_t^I - \mathcal{T}_{t-1}^I$, i.e., we use the change in the daily turnover rate averaged over all traded stocks as the dependent variable.

The estimated effects of monetary policy announcements on the daily marketwide NYSE turnover rate are reported in the second row of Table 1. According to the E-based estimate, a 100 bp increase in the policy rate causes a change in the level of the marketwide turnover rate on the day of the policy announcement equal to $-.0021$.²⁵ The daily marketwide turnover rate for our sample period is $.0048$ (i.e., on average, stocks turn over 1.22 times during a typical year composed of 252 trading days), which means that according to the E-based estimate, an increase in the policy rate of 25 bps causes a reduction in the marketwide turnover rate on the day of the policy announcement of about 10 percent of its typical level. The HFIV estimate for a 100 bp increase in the policy rate is $-.0052$, implying that a 25 bp increase in the policy rate causes a reduction in the marketwide turnover rate of about 27 percent of its typical level.

5.3 Disaggregative announcement-day effects

Another way to inspect the turnover-liquidity transmission mechanism of monetary policy is to exploit the cross-sectional variation in turnover rates that exists across stocks. Our theory implies that the magnitude of the change in the stock return induced by a change in the policy rate will depend on the turnover liquidity of the stock (e.g., as measured by the turnover rate of the stock). To test this prediction, we sort stocks into portfolios according to their turnover liquidity, as follows. For each FOMC announcement date, t , we calculate \mathcal{T}_t^s as the average turnover rate of an individual stock s over all trading days during the four weeks prior to the day of the policy announcement. We then sort all stocks into 20 portfolios by assigning stocks with \mathcal{T}_t^s ranked between the $[5(i-1)]^{\text{th}}$ percentile and $(5i)^{\text{th}}$ percentile to the i^{th} portfolio, for $i = 1, \dots, 20$. Hence, the average turnover rate over the four-week period prior to the announcement date for a stock in the i^{th} portfolio is at least as large as that of a stock in the $(i-1)^{\text{th}}$ portfolio. In Table 2, the column labeled “Turnover” reports the annual turnover rate

²⁵The R^2 indicates that 3 percent of the variance of the daily turnover rate in days of FOMC policy announcements is associated with unexpected changes in monetary policy.

(based on 252 trading days per year) corresponding to each of the 20 portfolios. For example, portfolio 1 turns over .17 times per year while portfolio 20 turns over 3.57 times per year.²⁶

For each of the 20 portfolios, Table 2 reports the E-based, H-based, and HFIV estimates of the announcement-day responses of the return to a 1 percentage point (pp) increase in the policy rate. All the estimates are negative, as predicted by the theory. Also, the magnitude of the (statistically significant) estimates increases with the turnover liquidity of the portfolio. For example, according to the HFIV estimates, a 1 bp increase in the policy rate causes a decrease of 6.44 bps in the return of portfolio 1 and a decrease of 16.40 bps in the return of portfolio 20. For all three estimation methods, the relative differences in responses across portfolios are of similar magnitude. For example, the response of the return of the most liquid portfolio is about 2.5 times larger than the response of the least liquid portfolio.²⁷ Figure 2 shows the announcement-day returns of portfolio 1 (the crosses) and portfolio 20 (the circles), along with their respective fitted lines. The larger magnitude of the response of the more liquid portfolio is evident.

As an alternative way to estimate the heterogeneous responses of returns to monetary policy shocks for stocks with different turnover liquidity, we ran an event-study regression of individual stock returns (for the universe of stocks listed in the NYSE) on changes in the policy rate, an interaction term between the change in the policy rate and individual stock daily turnover rate, and several controls. As before, Δi_t denotes the monetary policy shock on policy announcement day t (measured by the change between day t and day $t - 1$ in the 3-month Eurodollar futures contract with nearest expiration after the day t FOMC policy announcement), and \mathcal{T}_t^s is the average turnover rate of the individual stock s over all the trading days during the four weeks prior to the day of the policy announcement of day t . Let Δi and \mathcal{T} denote the sample averages of Δi_t and \mathcal{T}_t^s , respectively, and define $\overline{\mathcal{T}_t^s} \equiv (\mathcal{T}_t^s - \mathcal{T})$ and $\overline{\Delta i_t} \equiv (\Delta i_t - \Delta i)$. The regression

²⁶Our motivation for constructing these liquidity-based portfolios is twofold. First, at a daily frequency, *individual* stock returns are extremely noisy; by grouping stocks into portfolios based on some characteristic(s) related to returns, it becomes possible to see average return differences. Second, stock-specific turnover measures are time-varying, i.e., the turnover rate of a particular stock may change over time. Bernanke and Kuttner (2005) also examine the responses of more disaggregated indices to monetary policy shocks. Specifically, they estimate the responses of 10 industry portfolios constructed from CRSP returns as in Fama and French (1988) but find that the precision of their estimates is not sufficient to reject the hypothesis of an equal reaction for all 10 industries.

²⁷In Appendix B (Section B.3), we report similar results from an alternative procedure that sorts stocks into portfolios according to the strength of individual stock returns to changes in an aggregate (marketwide) measure of turnover. This alternative sorting criterion allows us to control for other differences across stocks, such as the conventional risk factors used in empirical asset-pricing models.

we fit is

$$\begin{aligned} \mathcal{R}_t^s = & \beta_0 + \beta_1 \Delta i_t + \beta_2 \mathcal{T}_t^s + \beta_3 \overline{\mathcal{T}_t^s} \times \overline{\Delta i_t} \\ & + D_s + D_t + \beta_4 (\Delta i_t)^2 + \beta_5 (\mathcal{T}_t^s)^2 + \varepsilon_{st}, \end{aligned} \quad (20)$$

where D_s is a stock fixed effect, D_t is a quarterly time dummy, and ε_{st} is the error term corresponding to stock s on policy announcement day t . The time dummies control for omitted variables that may affect the return of all stocks in the NYSE over time. The stock fixed effects control for the effects that permanent stock characteristics not included explicitly in the regression may have on individual stock returns. We include the interaction term $\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$ to estimate how the effect of changes in the policy rate on individual stock returns varies across stocks with different turnover liquidity. The coefficient of interest is β_3 , i.e., we want to test whether changes in the policy rate affect individual stock returns through the stock-specific turnover-liquidity channel. The estimate of β_3 can help us evaluate whether increases (reductions) in the policy rate cause larger reductions (increases) in returns of stocks with a larger turnover rate, i.e., whether $\beta_3 < 0$.

Table 3 reports the results from estimating nine different specifications based on (20). Specification (I) excludes D_s , D_t , the interaction term, $\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$, and the squared terms, $(\Delta i_t)^2$ and $(\mathcal{T}_t^s)^2$. Specification (II) adds the interaction term to specification (I). Specification (III) adds D_s to specification (II). Specification (IV) adds D_t to specification (II). Specification (V) adds D_s to specification (IV). Specifications (VI), (VII), (VIII), and (IX) each add the squared terms $(\Delta i_t)^2$ and $(\mathcal{T}_t^s)^2$ to specifications (II), (III), (IV), and (V), respectively. In all specifications, all estimates are significant at 1 percent level.

The estimates of β_1 lie near -5.5 in all specifications, implying that a 1 bp increase in the policy rate reduces the return of a stock with average turnover by about 5.5 bps on the day of the policy announcement.²⁸ The estimate of interest, β_3 , is large and negative in all specifications. The negative and statistically significant estimates of β_3 indicate that the magnitude of the negative effect of unexpected changes in the policy rate on announcement-day equity returns is larger for stocks with higher turnover liquidity. To interpret the magnitude of the estimates, consider a stock A with a daily turnover rate equal to .014 (i.e., a stock in liquidity portfolio 20) and an equity B with an annual turnover rate equal to .0007 (i.e., a stock in liquidity portfolio 1). Then, for example, according to specification (IX), the estimate of β_3 is -487 ,

²⁸Recall the average daily turnover in our sample is .0048.

implying that a 1 bp increase in the policy rate reduces the announcement-day return by $\beta_1 + 2\beta_4 + \beta_3 (\mathcal{T}_t^A - \mathcal{T}) \approx -10$ bps for equity A and by $\beta_1 + 2\beta_4 + \beta_3 (\mathcal{T}_t^B - \mathcal{T}) \approx -3$ bps for equity B . These estimates are quite close to the E-based estimates for portfolio 20 and for portfolio 1 reported in Table 2. Together with the findings reported in Table 1 and Table 2, the results in Table 3 provide additional evidence that turnover liquidity is a quantitatively important channel that transmits monetary policy shocks to asset prices.²⁹

5.4 Dynamic effects

In the previous section we documented the effect of monetary policy shocks on equity returns and turnover on the day the policy announcement takes place. While the turnover liquidity channel highlighted by our theory can generate the effects on announcement days documented in the previous section, the theoretical channel is eminently dynamic. In the theory, *persistent* changes in the nominal rate affect stock returns because they imply persistent changes in the future resale value of the stock. To study the dynamic effects of monetary policy on prices and turnover rates, we conduct a vector autoregression (VAR) analysis on the sample consisting of all trading days between January 3, 1994 and December 31, 2007.

The baseline VAR we estimate consists of three variables, i.e., $\{i_t, \mathcal{R}_t^I, \mathcal{T}_t^I\}$, where i_t , \mathcal{R}_t^I , and \mathcal{T}_t^I are the daily measures of the policy rate, the stock return, and turnover described in Section 5.1 and Section 5.2.³⁰ The lag length is set to 10.³¹ To identify the effects of monetary policy shocks, we apply an identification scheme based on an external high-frequency instrument.³²

²⁹In Appendix 5.2 (Section D.2) we show that our estimates of β_3 based on (20) are robust to including a number of additional controls, such as sensitivity to the three most common Fama-French factors, industry dummies, and a firm-specific measure of leverage (reliance on bank debt).

³⁰In Section 5.2, we used the change in the 3-month Eurodollar futures rate on the day of the FOMC announcement as a proxy for the unexpected component of the change in the true policy rate, i.e., the *effective federal funds rate*. In this section, we instead regard the 3-month Eurodollar futures rate as the policy rate itself. We do this because, at a daily frequency, the effective federal funds rate is very volatile for much of our sample, e.g., due to institutional considerations, such as “settlement Wednesdays.” The path of the 3-month Eurodollar futures rate is quite similar to the effective federal funds rate, but it does not display the large regulation-induced weekly swings. In any case, we have also performed the estimation in this section using the daily effective federal funds rate instead of the Eurodollar futures rate, and the results for returns and turnover are quite similar.

³¹The Akaike information criterion (AIC) suggests 10 lags, while Schwarz’s Bayesian information criterion (SBIC) and the Hannan and Quinn information criterion (HQIC) suggest 5 lags. We adopted the formulation with 10 lags, but both formulations deliver similar estimates.

³²See Appendix B (Section B.4.1) for details. The basic idea of structural vector autoregression (SVAR) identification using instruments external to the VAR can be traced back to Romer and Romer (1989) and has been adopted in a number of more recent papers, including Cochrane and Piazzesi (2002), Hamilton (2003), Kilian (2008a, 2008b), Stock and Watson (2012), Mertens and Ravn (2013), and Gertler and Karadi (2015).

Figure 3 reports the impulse responses of the policy rate, the average *cumulative* stock return between day t and day $t + j$ defined by $\bar{\mathcal{R}}_{t,t+j}^I \equiv \prod_{s=1}^j \mathcal{R}_{t+s}^I$, and the average turnover rate, to a 1 bp increase in the policy rate.³³ The 99 percent confidence intervals for $\{i_t, \mathcal{R}_t^I, \mathcal{T}_t^I\}$ are computed using a recursive wild bootstrap based on 10,000 replications.³⁴ The top and bottom rows show responses for forecast horizons of 30 days and 120 days, respectively. The path of the policy rate is very persistent (it remains significantly above the level prevailing prior to the shock for about 18 months). The middle panels in Figure 3 show the response of daily cumulative stock returns. On impact, in response to the 1 bp unexpected increase in the nominal rate, the stock return falls by about 9.4 bps. The magnitude of this response on the day of the policy shock is basically the same as the HFIV point estimate reported in Table 1. The negative effect on the stock price is persistent (the upper bound of the 99 percent confidence remains below zero for about 30 days). The right panels in Figure 3 show the response of the level of the daily turnover rate. On impact, a 1 bp surprise increase in the nominal rate causes a change in the level of the turnover rate equal to $-.00005$, which is the same as the HFIV point estimate reported in Table 1. According to the estimated impulse response, it takes about 1 day for the turnover rate to recover half of the initial drop. However, beyond that point, the negative effect of the increase in the policy rate on turnover is persistent (e.g., it takes 43 days for it to become statistically insignificant).

In order to inspect the turnover-liquidity transmission mechanism further, we exploit the cross-sectional variation in turnover rates across stocks and carry out the same VAR analysis of this section but individually on each of 20 liquidity portfolios of stocks, sorted on turnover liquidity.³⁵ Figure 4 shows the estimated impulse responses (to a 1 bp unexpected increase in the policy rate) of the cumulative returns of each of the twenty liquidity portfolios for a forecast horizon of 30 days. In the figure, the darker impulse responses correspond to the portfolios with

³³The impulse response for the cumulative return illustrates the path of $\{\bar{\mathcal{R}}_{-1,j-1}^I\}$, where $j = 1, 2, \dots$ indexes the number of days after the policy announcement.

³⁴The procedure is described in Appendix B (Section B.4.2). See Gonçalves and Kilian (2004) for a formal econometric analysis of this method. We compute the confidence bands for $\{\bar{\mathcal{R}}_{t,t+j}^I\}$ by compounding the confidence bands of the return response $\{\mathcal{R}_t^I\}$ (i.e., in the same way we compute $\{\bar{\mathcal{R}}_{t,t+j}^I\}$ from $\{\mathcal{R}_t^I\}$).

³⁵In Section 5.3 we re-sorted stocks into liquidity portfolios for each day in our sample of FOMC announcement dates (based on the average daily turnover rate over the four weeks prior to each FOMC announcement). For the high-frequency VAR that we estimate in this section, stocks are resorted into one of 20 liquidity portfolios every day. On days with no FOMC announcement, the sorting is based on daily turnover rate. On FOMC announcement days, stocks are sorted based on their turnover rate two days prior to the announcement. Since the ranking of a given stock in terms of turnover tends to be quite persistent, all the sorting schemes described here deliver similar results.

higher turnover liquidity (e.g., the lightest impulse response is for portfolio 1 and the darkest, for portfolio 20). To further illustrate the results, Figure 5 reports the impulse responses and the corresponding 99 percent confidence intervals of the cumulative portfolio return to a 1 bp unexpected increase in the policy rate for a forecast horizon of 30 days, for portfolios 1, 10, and 20. Notice that the announcement-day portfolio-by-portfolio responses estimated by the VAR line up well with the portfolio-by-portfolio HFIV estimates reported in Table 2. As in Section 5.3, we again find that on the announcement day, the negative responses of returns to an unexpected increase in the nominal rate tend to be larger in magnitude for portfolios with higher turnover liquidity. However, here these responses appear to be estimated much more precisely than in Table 2.³⁶ Also, notice that—as will be the case in the quantitative theory—the price responses of the portfolios with larger turnover liquidity are not only larger in magnitude on impact, but also tend to be more persistent.³⁷

In this section we have provided empirical evidence consistent with the turnover-liquidity transmission mechanism of monetary policy: a persistent increase in the nominal rate reduces the resale value of stocks, and this reduction in *turnover liquidity* is reflected in a persistent price reduction and higher future stock returns.³⁸

6 Quantitative analysis

The theoretical results we used to motivate the empirical analysis of Section 5 (e.g., part (i) of Proposition 2, part (i) of Proposition 3, and parts (i) and (ii) of Proposition 5) correspond to

³⁶Aside from the fact that the VAR specification is more flexible than (19), our VAR estimation also relies on the HFIV identification scheme. In fact, notice that even for the simple specification (19), Table 1 and Table 2 show that in general, the HFIV identification strategy by itself already delivers estimates that are more precise and more statistically significant than the E-based and H-based estimates.

³⁷Based on the announcement-day evidence alone, one might conjecture that the differential return response on impact across liquidity portfolios may simply reflect that the prices of stocks with lower turnover liquidity take longer to react to the FOMC shock. This conjecture, however, does not seem to be supported by the VAR evidence in Figure 4 and Figure 5. The conjecture is also not supported by the additional regression analysis we carry out in Appendix D (Section D.1), where we estimate the effect of an unexpected policy shock on day t on $\bar{\mathcal{R}}_{t-1,t+1}^I$, i.e., the cumulative stock return for the two-day horizon after the policy announcement.

³⁸Bernanke and Kuttner (2005) is one of a few papers that has tried to identify the economic forces behind the negative effect of nominal rate increases on stock returns. They use a VAR to decompose excess equity returns into components attributable to news about dividends, real interest rates, and future excess returns. They find the component associated with future excess returns accounts for the largest part of the response, i.e., an increase in the policy rate lowers stock prices mostly by increasing the expected equity premium. Bernanke and Kuttner speculate this could come about via some unspecified mechanism through which tight money increases the riskiness of stocks (or decreases the investor’s willingness to bear risk). The turnover-liquidity mechanism we have identified is consistent with Bernanke and Kuttner’s decomposition.

a permanent, unanticipated increase in the nominal rate, which while suggestive, is somewhat different from the policy shocks underlying the empirical estimates of Section 5. Thus in order to assess the predictions and quantitative performance of the theory, in this section we formulate, calibrate, and simulate a generalized version of the model of Section 2.

We generalize the model along three dimensions. First, we incorporate aggregate uncertainty in the path of monetary policy, represented by changes in the nominal interest rate implemented via open-market operations. This extension allows us to consider theoretical experiments that resemble more closely what goes on in financial markets, in the sense that while investors may be surprised by the timing and size of changes in the nominal rate, they take into account a probability distribution over future paths of the monetary policy so these changes are not entirely unexpected. Second, we extend the model so that the innovations to the nominal policy rate may be associated with innovations to the expected inflation rate (as in the propositions of Section 4), as well as with innovations to the real interest rate. This extension allows us to quantify the turnover-liquidity mechanism for settings where changes in the nominal rate may be associated with changes in the expected inflation rate as well as with changes in the real rate. Third, we extend the model to the case of multiple equity classes that differ in their liquidity properties. This extension allows us to provide additional evidence for the turnover-liquidity mechanism by exploiting the cross-sectional heterogeneity and using it to assess the quantitative theoretical effects of monetary policy on the cross section of equity returns.

6.1 Generalized model

There are N equity classes, each indexed by $s \in \mathbb{N} = \{1, 2, \dots, N\}$. The outstanding quantity of equity shares of class s is A^s . Since the focus is on the implication of liquidity differences across equity classes, we assume each class gives the same dividend y_t , which follows the same stochastic process described in the one-asset model of Section 2. An investor's period t valuation of the dividend of any equity is distributed independently over time and across investors, with cumulative distribution function G , just as in the one-asset setup.

We model liquidity differences as follows. In each round of OTC trade, each investor can trade equity class $s \in \mathbb{N}$ with probability $\alpha^s \in [0, 1]$. The event that the investor is able to trade equity class s is independent of the event that he is able to trade any other equity class $n \in \mathbb{N}$. We interpret α^s as the probability that an individual investor contacts a dealer with whom he can trade equity class s . This captures the idea that dealers are specialized in trading

a particular equity class.³⁹ In the OTC trading round there is a competitive interdealer market for each equity class. These markets are segmented in the following sense: (i) in the OTC trading round, equity s can only be traded in market s , and (ii) at the beginning of the period, investors partition the money they will use for trading stocks in the first subperiod into a cash portfolio with N components, i.e., $\{a_t^{ms}\}_{s \in \mathbb{N}}$, where a_t^{ms} is the amount of money the investor chooses to have available to trade equity class s in the OTC market of period t . Each investor makes this cash rebalancing decision after having observed the realization of the aggregate state, but before learning which equity classes he will be able to trade, and before learning his individual valuation of the dividend (the last two assumptions keep the ex post number of investor types to a minimum). For simplicity, in this section we assume dealers do not hold asset inventories overnight (and without loss, also that they do not hold money overnight).

In Section 2, we assumed a constant growth rate of the money supply, i.e., $A_{t+1}^m = \mu A_t^m$, where $\mu \in \mathbb{R}_{++}$. In this section we broaden the analysis of monetary policy along three dimensions: (a) We allow the monetary authority to inject or withdraw money not only with lump sum taxes, but also via open-market operations. This is a more realistic implementation of monetary policy, and makes the theory more flexible in that it can encompass a wider range of responses to monetary policy shocks. (b) We model monetary policy as a stochastic process. This allows the theory to exhibit monetary policy shocks that resemble the policy surprises in the empirical analysis of Section 5. (c) We allow monetary policy to affect market outcomes by influencing the nominal rate through both of its components: the expected inflation rate, and the real interest rate. This allows us to assess the robustness of the turnover-liquidity mechanism to different degrees of passthrough from nominal rates to real rates. In summary, we will consider general monetary policy processes that consist of three components: an open-market operation, a change in expected inflation, and a change in the real rate. Each of these components of the monetary policy process is modeled as follows.

In the first subperiod, each investor can always trade in a competitive market where the

³⁹In the theory, differences in α , θ , or G all give rise to differences in turnover across assets. We focus on differences in α because it is conceptually the simplest and analytically the most direct way to construct asset classes that differ in turnover liquidity. However, one could carry out the theoretical analysis by constructing asset classes based on differences in G and θ . Differences in G work similarly to differences in α (see the equivalence result proved in Proposition 10, Appendix A). With regard to differences in θ , in a large class of models that includes this one, Duffie et al. (2005) and Lagos and Rocheteau (2009), the equilibrium asset price does not depend on α and θ independently, but on their product, $\alpha\theta$. Thus, for asset-pricing purposes, differences in α can be interpreted as capturing differences in the trading probability or in the bargaining power. The quantitative response of turnover to money shocks will typically depend on whether assets differ in α or θ , however.

monetary authority sells B_t one-period risk-free pure-discount nominal bonds. A bond issued in the first subperiod of t yields one dollar with certainty in the following subperiod. The dollar price of a bond in this market is denoted q_t . The bond market is segmented in the same way as the markets for equity shares, i.e., at the beginning of period t , having observed the realization of the monetary policy variables (but before knowing which equity classes he will be able to trade or his dividend valuation), each investor chooses a partition of his money holdings, $\{a_t^{ms}\}_{s \in \bar{\mathbb{N}}}$, where $\bar{\mathbb{N}} \equiv \mathbb{N} \cup \{b\}$, and a_t^{mb} denotes the amount of money the investor chooses to have available to trade bonds in the first subperiod of t . The size of the bond issue, B_t , relative to the size of the beginning-of-period money supply, A_t^m , is denoted ω_t . That is, if there are A_t^m dollars outstanding at the beginning of period t , in the bond market of the first subperiod t the government sells claims to $B_t = \omega_t A_t^m$ dollars payable in the following subperiod.

The beginning-of-period money supply evolves according to $A_{t+1}^m = [1 + (1 - q_t)\omega_t] \tilde{\mu}_t A_t^m$, where $\tilde{\mu}_t \in \mathbb{R}_{++}$ denotes the growth rate of the money supply between the end of period t and the beginning of period $t + 1$ (implemented via lump-sum transfers in the second subperiod of t). The monetary authority can implement any arbitrary process for the growth rate of the beginning-of-period money supply, i.e., can set, $A_{t+1}^m = \mu_t A_t^m$ for any positive path $\{\mu_t\}_{t=1}^\infty$, despite the random changes in the money supply induced by the open-market operations.⁴⁰ Finally, to allow for the possibility that monetary policy can affect outcomes by influencing the real rate as well as expected inflation, we generalize the constant interest rate r of Section 2 to a stochastic process $\{r_t\}_{t=1}^\infty$.

To summarize, we model monetary policy as a stochastic process $\{\tau_t\}_{t=1}^\infty$, where $\tau_t \equiv (\omega_t, \mu_t, r_t)$. This formulation is general enough to encompass situations where monetary policy amounts to changing expected inflation (as in monetarist models) as well as settings where monetary policy amounts to directly influencing real rates (as in New Keynesian models). We assume $\{\tau_t\}_{t=1}^\infty$ follows a Markov chain with transition matrix $\sigma_{ij} = \Pr(\tau_{t+1} = \tau_j | \tau_t = \tau_i)$, where $\tau_i \equiv (\omega_i, \mu_i, r_i) \in \mathbb{R}_{++}^3$ and $\tau_j \equiv (\omega_j, \mu_j, r_j) \in \mathbb{R}_{++}^3$ for $i, j \in \mathbb{M} = \{1, \dots, M\}$. The realization of τ_t is known at the beginning of period t .

We specialize the analysis to recursive equilibria in which prices and portfolio decisions are time-invariant functions of an aggregate state vector that follows a time-invariant law of motion. The state vector is $\mathbf{x}_t = (A_t^m, y_t, \tau_t) \in \mathbb{R}_+^5$. Asset prices in a recursive equilibrium will be

⁴⁰Specifically, $\tilde{\mu}_t = \mu_t / [1 + (1 - q_t)\omega_t]$ implies $A_{t+1}^m = \mu_t A_t^m$ for any $\{\mu_t\}_{t=1}^\infty$. The government budget constraint is $B_t + T_t / \phi_t^m = A_{t+1}^m - (A_t^m - q_t B_t)$, so the real lump-sum transfer (expressed in terms of the second-subperiod consumption good) needed to implement $A_{t+1}^m = \mu_t A_t^m$ is $T_t = [(\mu_t - 1) - (1 - q_t)\omega_t] \phi_t^m A_t^m$.

denoted $\phi_t^s = \phi^s(\mathbf{x}_t)$, $\bar{\phi}_t^s = \bar{\phi}^s(\mathbf{x}_t)$, $\phi_t^m = \phi^m(\mathbf{x}_t)$, $p_t^s = p^s(\mathbf{x}_t)$, $q_t = q(\mathbf{x}_t)$, and $\varepsilon_t^{s*} = \varepsilon^{s*}(\mathbf{x}_t)$. Let A_t^{mk} denote the amount of money that investors have available to trade asset $k \in \bar{\mathbb{N}}$ at the beginning of period t (i.e., the bond, if $k = b$, or equity, if $k \in \mathbb{N}$). The laws of motion for the state variables A_t^m , y_t , and τ_t are exogenous (as described above), while $A_t^{mk} = \Psi^k(\mathbf{x}_t)$ for $k \in \bar{\mathbb{N}}$, where the decision rule Ψ^k is determined in equilibrium. Suppose $\mathbf{x}_t = (A_t^m, y_t, \tau_t)$ and focus on a recursive equilibrium with the property that real prices are linear functions of the aggregate dividend, and $\Psi^k(\mathbf{x}_t) = \lambda_i^k A_t^m$ for all $k \in \bar{\mathbb{N}}$, where $\lambda_i^s \in [0, 1]$ denotes the fraction of the beginning-of-period money holdings that investors have chosen to have available to trade asset class k in the OTC round of period t . Then, $\phi^s(\mathbf{x}_t) = \phi_i^s y_t$, $\bar{\phi}^s(\mathbf{x}_t) \equiv p^s(\mathbf{x}_t) \phi^m(\mathbf{x}_t) = \bar{\phi}_i^s y_t$, $\phi^m(\mathbf{x}_t) A_t^m = Z_i y_t$, $q(\mathbf{x}_t) = q_i$, and $\varepsilon^{s*}(\mathbf{x}_t) \equiv [\bar{\phi}^s(\mathbf{x}_t) - \phi^s(\mathbf{x}_t)]/y_t = \bar{\phi}_i^s - \phi_i^s \equiv \varepsilon_i^{s*}$.

In Appendix C (Section C.3), we show that an equilibrium is characterized by a vector $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s\}_{i \in \mathbb{M}, s \in \bar{\mathbb{N}}}$ of $M(3N + 2)$ unknowns that solves the following system with $M(3N + 2)$ independent equations:

$$\phi_i^s = \frac{\bar{\gamma}\delta}{1 + r_i} \sum_{j \in \mathbb{M}} \sigma_{ij} \left[\bar{\varepsilon} + \phi_j^s + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon_j^{s*}} (\varepsilon_j^{s*} - \varepsilon) dG(\varepsilon) \right] \quad (21)$$

$$Z_i = \frac{\bar{\gamma}}{(1 + r_i) \mu_i} \sum_{j \in \mathbb{M}} \sigma_{ij} \left[1 + \alpha^s \theta \int_{\varepsilon_j^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_j^{s*}}{\varepsilon_j^{s*} + \phi_j^s} dG(\varepsilon) \right] Z_j \quad (22)$$

$$\max(\omega_i/\lambda_i^b, 1) = 1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon) \text{ for all } (i, s) \in \mathbb{M} \times \mathbb{N} \quad (23)$$

$$Z_i \lambda_i^s = \frac{G(\varepsilon_i^{s*}) A^s}{1 - G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s) \text{ for all } (i, s) \in \mathbb{M} \times \mathbb{N} \quad (24)$$

$$1 - \lambda_i^b = \sum_{s \in \mathbb{N}} \lambda_i^s \text{ for all } i \in \mathbb{M}. \quad (25)$$

In the following subsections, we calibrate and simulate this model to assess the ability of the theory to account for the empirical findings reported in Section 5. Before doing so, it is useful to define the theoretical analogues of the variables we studied in the empirical section.

The return of stock s at date $t + 1$ is $\mathcal{R}_{t+1}^s = \bar{\phi}_{t+1}^s/\phi_t^s - 1$, where $\bar{\phi}_t^s \equiv p_t \phi_t^m = \phi_t^s + \varepsilon_t^{s*} y_t$ is the *cum dividend price* of equity at date t defined in Section 3. The real return from holding a dollar between the end of period t and the end of period $t + 1$ is $\phi_{t+1}^m/\phi_t^m \equiv (1 + \pi_{t+1})^{-1}$, where π_{t+1} denotes the (net) inflation rate between t and $t + 1$. In a recursive equilibrium, suppose

the state is $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_j)$ at t , and $\mathbf{x}_{t+1} = (\mu_j A_t^m, y_{t+1}, \boldsymbol{\tau}_k)$ at $t + 1$, then

$$1 + \mathcal{R}_{t+1}^s = \frac{\phi_k^s + \varepsilon_k^{s*}}{\phi_j^s} \frac{y_{t+1}}{y_t}$$

$$1 + \pi_{t+1} = \frac{Z_j}{Z_k} \frac{y_t}{y_{t+1}} \mu_j.$$

So far we have implicitly assumed that A^s , i.e., all outstanding equity shares of class s , are actively traded every day. In actual markets, however, a fraction of the outstanding equity shares are seldom traded (stocks held in 401(k) accounts, for example). Our theory remains unchanged if we replace A^s with κA^s for some $\kappa \in [0, 1]$ that represents the proportion of the universe of outstanding stocks that are actively traded, and think of the remaining $(1 - \kappa) A^s$ as being held by nontraders outside the model. In an equilibrium in which dealers do not hold assets (as is the case in this section), trade volume for asset class s at date t is $\mathcal{V}_t^s = 2\alpha^s G(\varepsilon_t^{s*}) \kappa A^s$. A conventional measure of trade volume is the *turnover rate* used in the empirical work of Section 5.1. According to the theory, the turnover rate on date t is

$$\mathcal{T}_t^s = \mathcal{V}_t^s / A^s = 2\alpha^s G(\varepsilon_t^{s*}) \kappa.$$

Naturally, a nonzero fraction of inactive stocks (i.e., $\kappa < 1$) lowers the *measured* level of the turnover rate.⁴¹ In a recursive equilibrium, suppose the state at date t is $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_j)$, then the turnover rate can be written as $\mathcal{T}_j^s = 2\alpha^s G(\varepsilon_j^{s*}) \kappa$. In the theory as in our empirical work, whenever we use an average, e.g., of equity returns or turnover rates across a set of stocks, we use the arithmetic average, e.g., $\mathcal{R}_t^I = \frac{1}{N} \sum_{s \in \mathbb{N}} \mathcal{R}_t^s$ and $\mathcal{T}_t^I = \frac{1}{N} \sum_{s \in \mathbb{N}} \mathcal{T}_t^s$ are the average return and the average turnover rate for the universe of stocks in the theory.

The (net) nominal rate on the government bond in state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_j)$ is $q(\mathbf{x}_t)^{-1} - 1 = \max(\omega_j / \lambda_j^b, 1) - 1 \equiv i_j$. Then (22) and (23) imply the Fisher equation (the generalization of (14))

$$1 = \sum_{k \in \mathbb{M}} \sigma_{jk} \frac{1 + i_k}{(1 + r_j)(1 + \bar{\pi}_{jk})} \quad (26)$$

where $\bar{\pi}_{jk} \equiv \mu_j Z_j / (\bar{\gamma} Z_k) - 1$ is the average inflation rate between state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_j)$ and state $\mathbf{x}_{t+1} = (\mu_j A_t^m, y_{t+1}, \boldsymbol{\tau}_k)$.

⁴¹The first column labeled “Turnover” in Table 2 reports the annual turnover rates corresponding to each of the 20 portfolios we studied in Section 5.3. Notice that the turnover rates appear to be quite low: even the top 5 percent most traded stocks are only traded about 3 times per year, on average, which suggests that the model should allow for the possibility of $\kappa < 1$.

6.2 Calibration

We think of one model period as being one day. We set $\theta = 1$ in our baseline and abstract from micro-level pricing frictions induced by bargaining. The dividend growth rate is independently lognormally distributed over time, with mean .04 and standard deviation .12 per annum (e.g., as documented in Lettau and Ludvigson (2005), Table 1). That is, $y_{t+1} = e^{x_{t+1}} y_t$, with $x_{t+1} \sim \mathcal{N}(\bar{\gamma} - 1, \Sigma^2)$, where $\bar{\gamma} - 1 = \mathbb{E}(\log y_{t+1} - \log y_t) = .04/365$ and $\Sigma = SD(\log y_{t+1} - \log y_t) = .12/\sqrt{365}$. The parameter δ can be taken as a proxy of the riskiness of stocks; a relatively low value ensures the monetary equilibrium exists even at relatively high inflation rates. We choose $\delta = (.7)^{1/365}$, i.e., a productive unit has a 70 percent probability of remaining productive each year. The number of outstanding shares of stocks of every class is normalized to 1, i.e., $A^s = 1$ for all $s \in \mathbb{N}$. We set $N = 20$ so the number of asset classes in the theory matches the number of synthetic liquidity portfolios considered in the cross-sectional analysis of Section 5.3.

We normalize $\alpha^{20} = 1$ and calibrate $\{\alpha^s\}_{s=1}^{19}$ so that the long-run time-average (under the invariant distribution of monetary policy shocks) of the equilibrium turnover rate of portfolio $s \in \{1, \dots, 19\}$ relative to portfolio 20 (i.e., $\bar{\mathcal{T}}^s/\bar{\mathcal{T}}^{20}$, where $\bar{\mathcal{T}}^s \equiv \lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T \mathcal{T}_t^s$) matches the ratio of the average turnover rate of the s^{th} and the 20^{th} synthetic liquidity portfolio in our sample. Idiosyncratic valuation shocks are drawn from a lognormal distribution. The parameters of the lognormal and the fraction of actively traded stocks, κ , are chosen so that under the baseline monetary policy process, in response to an unexpected innovation to the policy rate, the theory generates: (i) a marketwide stock return (i.e., \mathcal{R}_t^I) on the day of the policy change that matches the corresponding empirical HFIV estimate documented in Table 1, and (ii) a change in the marketwide turnover rate (i.e., \mathcal{T}_t^I) on the fifth day after the policy change that matches the corresponding empirical estimate from the VAR in Section 5.4.⁴²

We estimate the stochastic process for the nominal policy rate, $\{\hat{i}_t\}_{t=0}^{\infty}$, using data for the rate on the 3-month Eurodollar future contract. We formulate that the logarithm of the policy rate follows an AR(1) process, we estimate this process at a daily frequency for every trading day between January 3, 1994, and December 31, 2007, and approximate it with a 7-state Markov chain, $\{\hat{i}_j, [\hat{\sigma}_{jk}]\}_{j,k=1}^7$.⁴³ We then use this estimated policy process to calibrate the theoretical

⁴²This procedure delivers $\kappa = .016$, $\ln \varepsilon_t \sim \mathcal{N}(-0.2332, 1.5705)$, $\alpha^1 = .1218$, $\alpha^2 = .1707$, $\alpha^3 = .1972$, $\alpha^4 = .2224$, $\alpha^5 = .2438$, $\alpha^6 = .2590$, $\alpha^7 = .2748$, $\alpha^8 = .2939$, $\alpha^9 = .3121$, $\alpha^{10} = .3306$, $\alpha^{11} = .3492$, $\alpha^{12} = .3679$, $\alpha^{13} = .3899$, $\alpha^{14} = .4149$, $\alpha^{15} = 0.4445$, $\alpha^{16} = .4821$, $\alpha^{17} = .5284$, $\alpha^{18} = .6011$, $\alpha^{19} = .7151$.

⁴³Specifically, the process we estimate is $\ln i_t = (1 - \xi) \ln i_0 + \xi \ln i_{t-1} + \epsilon_t$, where ϵ_t is Gaussian white noise. With i_t denominated in bps, the estimates are $\xi = .9996695$, $\mathbb{E}(\ln i_t) = \ln i_0 = 5.990701$, and $\sqrt{\mathbb{E}(\epsilon_t^2)} =$

monetary policy process, $\langle (\omega_j, \mu_j, r_j), [\sigma_{jk}] \rangle_{j,k \in \mathbb{M}}$, as follows. We set $[\sigma_{jk}] = [\hat{\sigma}_{jk}]$, and choose the process of open-market operations, $\{\omega_j\}_{j \in \mathbb{M}}$, that implements an aggregate real value of money that is constant across states, i.e., $Z_j = Z$ for all $j \in \mathbb{M}$.⁴⁴ Then (26) implies $\iota_k \approx r_k + \pi_k$ for all $k \in \mathbb{M}$, where $\iota_k \equiv \sum_{j \in \mathbb{M}} \sigma_{kj} (1 + i_j)$ is the expected one-period-ahead nominal rate conditional on the current state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_k)$, and $\pi_k \equiv \mu_k / \bar{\gamma} - 1$ is the average inflation rate between state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_k)$ and any state \mathbf{x}_{t+1} . Let \bar{i} , \bar{r} , and $\bar{\pi}$, denote the empirical means of the nominal policy rate, the real interest rate, and the inflation rate, respectively. Over the sample period 1994-2007, the average nominal policy rate was .0447 and the average inflation rate was .0269, so (14) implies a real rate of .0178 per annum.⁴⁵ Hence, $1 + \bar{i} = (1.0447)^{1/365}$, $1 + \bar{r} = (1.0178)^{1/365}$, and $1 + \bar{\pi} = (1.0269)^{1/365}$. For each $k \in \mathbb{M}$, we set $r_k = \bar{r} + w \hat{\eta}_k$ and $\pi_k \equiv \bar{\pi} + (1 - w) \hat{\eta}_k$, where $\hat{\eta}_k \equiv \hat{i}_k - \bar{i}$, and $w \in [0, 1]$ indexes the degree of passthrough from nominal rates to real rates. We use $w = .8$ as baseline, which implies a 100 bp increase in the nominal rate is associated with a 80 bp increase in the real rate and a 20 bp increase in expected inflation.⁴⁶

6.3 Simulation

In this section we conduct two experiments to assess the ability of the theory to match the evidence documented in Section 5. In both experiments, we simulate the calibrated model as

.0114289. Hence the estimated mean and standard deviation of the nominal rate, i_t , are $\mathbb{E}(i_t) = 441$ and $\sqrt{\text{Var}(i_t)} = \sqrt{\frac{\mathbb{E}(\epsilon_t^2)}{1 - \xi^2}} = 206.2516$. The estimated AR(1) process is very persistent so, as suggested by Galindev and Lkhagvasuren (2010), we use the Rouwenhorst method to compute the approximating Markov matrix and states. The code for the Rouwenhorst method is also from Galindev and Lkhagvasuren (2010).

⁴⁴The precise process of open-market operations is described in Appendix C (Proposition 12 in Section C.3). This policy implies the real price of money does not change at the times when monetary policy switches states. Consider a state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_i)$. The relevant nominal prices in the model are the dollar price of the second-subperiod consumption good, $1/\phi^m(\mathbf{x}_t) = A_t^m / (Z_i y_t)$, and the dollar price of an equity share, $p^s(\mathbf{x}_t) = A_t^m (\varepsilon_i^{s*} + \phi_i^s) y_t / (Z_i y_t)$. Under the policy $\{\omega_j\}_{j \in \mathbb{M}}$ that implements $Z_j = Z$ for all $j \in \mathbb{M}$, $\phi^m(\mathbf{x}_t)$ is invariant to monetary policy surprises on impact, and $p^s(\mathbf{x}_t)$ responds only if the policy surprise has an effect on the *real* cum-divided equity price. Thus this process of open-market operations makes our flexible-price model consistent with the fact that nominal prices in the data typically do not jump when there is a surprise change in the nominal policy rate, even when the policy shock may imply a change in the path of expected inflation.

⁴⁵As in Section, 5.1 for the policy rate we use the 3-month Eurodollar futures rate (series IEDCS00 produced by the CME Group available via Datastream). The annual average inflation rate is imputed as $[\text{CPI}(\text{January}_{2008}) / \text{CPI}(\text{January}_{1994})]^{1/14} - 1$, where $\text{CPI}(\text{Month}_{Year})$ is monthly CPI index available from FRED at <https://fred.stlouisfed.org/series/CPIAUCSL>.

⁴⁶This choice is guided by the passthrough estimates in Gertler and Karadi (2015) at a two-year horizon. As a robustness check, we have also set $w = 1$ and recalibrated the model to fit the same data targets as the baseline calibration, and found that the quantitative performance of the theory is very similar to the case with $w = .8$. In Appendix D (Section D.6) we report results for the case with $w = 0$.

follows. First, compute the equilibrium functions characterized by (21)-(25). Second, simulate 1,000 samples of the dividend, each of length equal to our data sample. Then set the path of the nominal rate in the model equal to the actual empirical path of the policy rate used in our empirical work. Finally, compute the equilibrium path of the model 1,000 times (one for each realization of the simulated dividend path), and for each simulated equilibrium path, compute the average daily equity return for each asset class.

6.3.1 Experiment 1: Disaggregative announcement-day effects

The first experiment is the model analogue of the cross-sectional analysis of Section 5.2. For each of the 20 asset classes, we run an event-study regression for announcement-day returns 1,000 times (one for each of the 1,000 simulated equilibrium paths for daily stock return for that particular asset class). The results are illustrated in Figure 6, which reports the empirical HFIV estimates from Table 2 along with the regression estimates from the simulated model.⁴⁷ For each theoretical portfolio, the value displayed in Figure 6 is the average E-based estimate over the model 1,000 simulations. The 99% confidence intervals for the theoretical estimates are constructed using the distribution of estimates from the 1,000 model simulations. The 99 percent confidence intervals for the empirical estimates are from the HFIV regressions from Section 5.3. The model was calibrated so that the *marketwide* response to the policy shock on the announcement day matches the empirical HFIV estimate of Table 1. We are interested in whether the theory can account for the profile of returns across stocks with different turnover liquidity—the hallmark of the turnover-liquidity transmission mechanism. Figure 6 shows the theory is able to generate most of the announcement-day tilting in cross-sectional returns. The fit is excellent for the first fourteen liquidity portfolios. For the six most liquid portfolios, the model predicts a bit less tilting than the data.

6.3.2 Experiment 2: Impulse responses

The second experiment is the model analogue of the VAR analysis of Section 5.4. Figure 7 reports the model-generated impulse responses for the policy rate, the cumulative marketwide stock return, and the average turnover rate to a 1 bp increase in the policy rate, along with the corresponding empirical impulse responses and 99 percent confidence intervals estimated

⁴⁷Since the monetary policy is exogenous in the model, the E-based estimates based on the synthetic data are not subject to the biases discussed in Section 5.2. For this reason, here we use the HFIV empirical estimates as a benchmark for comparison.

from actual data (those described in Section 5.4). The top and bottom panels show responses for forecast horizons of 30 days and 120 days, respectively. The path of the policy rate from the model is quite close to the empirical path. The middle panels show the response of the daily cumulative stock return. On impact, in response to the 1 bp unexpected increase in the nominal rate, the model stock return falls by 9.38 bps—the same as the HFIV estimate of Table 1, as targeted by the calibration. Since persistence (of the policy shock and turnover liquidity) is an essential element of the theoretical mechanism, we are interested in whether the model can account for the dynamics of the response of the cumulative return. The theoretical and empirical impulse responses for subsequent days after the policy shock remain quite close. For example, the theoretical impulse response can account for over 80% of the empirical response for the first 30 days, and for at least 66% of the empirical response for the subsequent 90 days.⁴⁸

The right panels of Figure 7 show the response of the level of the daily turnover rate. The model was calibrated so that the response of turnover on day 5 after the announcement matches the empirical estimate. On impact, in response to a 1 bp unexpected increase in the nominal rate, the turnover rate falls by -6.8502×10^{-6} in the model. The model response for turnover is about seven times smaller than the empirical estimate (-4.8692×10^{-5} according to the empirical impulse response). However, although the model response for turnover is much smaller on impact, it is very persistent and remains relatively close to the empirical response at longer horizons. For example, the difference between the empirical path for the turnover rate and the theoretical path becomes statistically insignificant for all days after day 3. Both the empirical and the theoretical responses are quite persistent. This persistent effect of policy on the turnover rate is consistent with a response in return that is quantitatively in line with the data, even though the announcement-day effect on turnover is much smaller than in the data.

7 Conclusion

We conclude by mentioning what we think are three promising avenues for future work. First, in the model we have presented, all asset purchases are paid for with outside money. In other words, the theory focuses on the relevant margin for settings, transactions, or traders for which credit limits have become binding. While arguably stark, we think this formulation is a useful benchmark to contrast with the traditional asset-pricing literature that abstracts from the role

⁴⁸The simulated theoretical cumulative return is -8.7 bp on day 30, and -7.7 bp on day 120. The estimated empirical cumulative return is -11.0 bp on day 30, and -11.7 bp on day 120.

of costly or scarce payment instruments. Having said this, we think it would be useful to extend the theory to allow for credit arrangements. The possibility of *buying on margin*, for example, is likely to interact with the monetary mechanisms we have emphasized here in interesting ways (see Lagos and Zhang (2019) for work along these lines). Second, given that trading frictions in the exchange process are at the center of the analysis (e.g., the likelihood of finding a counterparty, or the market power of dealers who intermediate transactions), it would be interesting to endogenize them (see Lagos and Zhang (2015) for work in this direction). Third, while we have focused on stocks in our empirical work, the transmission mechanism we have identified is likely to be operative—and possibly even more conspicuous—in markets for other assets, such as Treasury securities and assets that trade in more frictional over-the-counter markets.

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	E-based		H-based		HFIV	
	Estimate	Std. dev.	Estimate	Std. dev.	Estimate	Std. dev.
Return	-5.47 ^{***}	1.30	-11.31 ^{**}	4.53	-9.38 ^{***}	2.86
Turnover	-.0021 [*]	.0013	-.0015	.0034	-.0052 ^{***}	.0013

Table 1: Empirical response of NYSE marketwide stock returns and turnover to monetary policy. ^{***} denotes significance at the 1 percent level, ^{**} significance at the 5 percent level, ^{*} significance at the 10 percent level.

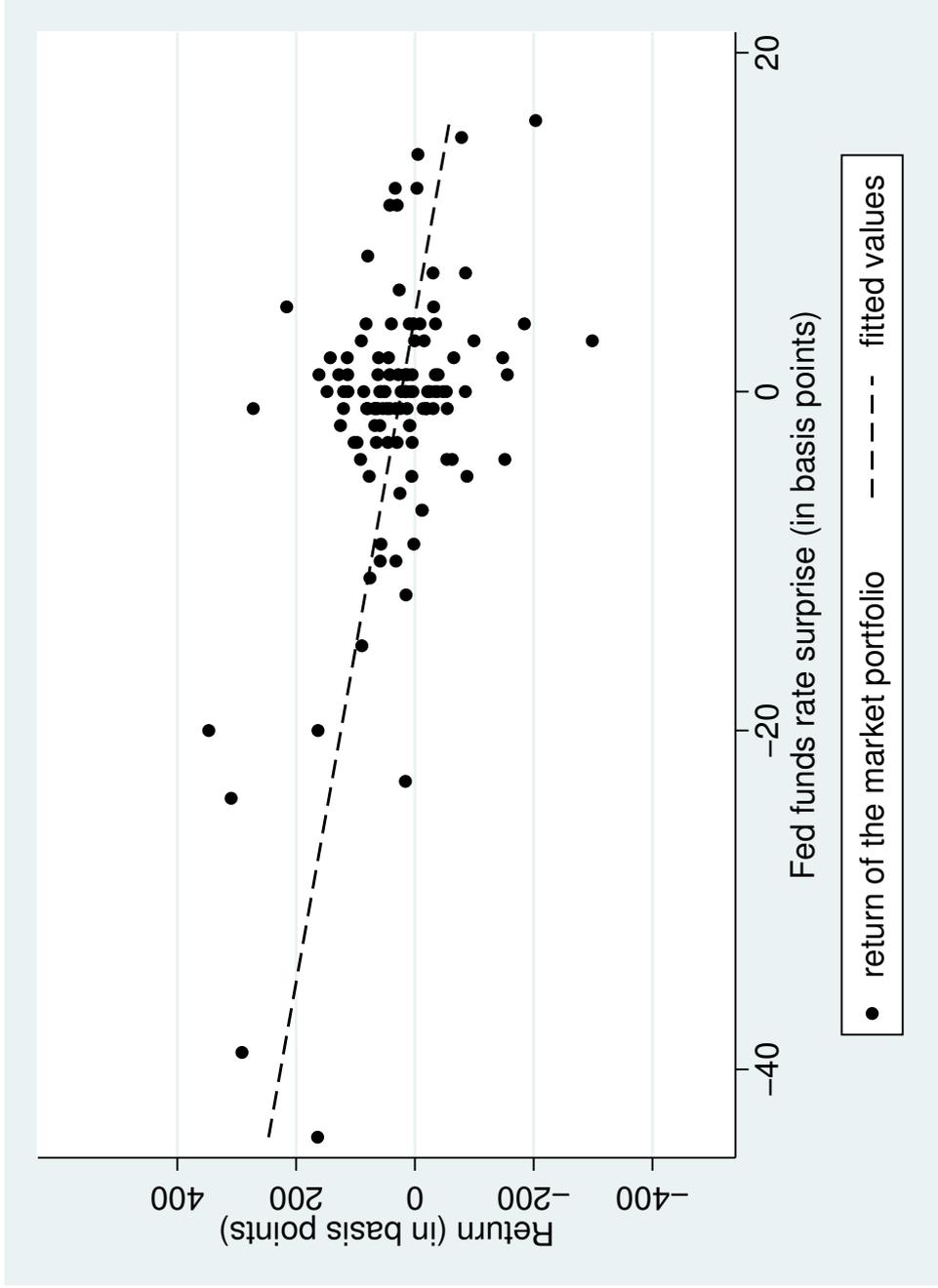


Figure 1: Unexpected component of the change in the policy rate on FOMC announcement dates and announcement-day marketwide NYSE stock returns.

Portfolio	Turnover	E-based			H-based			HFIV		
		Estimate	Std. dev.		Estimate	Std. dev.		Estimate	Std. dev.	
1	.17	-3.74***	0.98	-7.18***	2.76	-6.44***	1.80			
2	.32	-3.81***	1.03	-8.40**	3.66	-5.81***	2.03			
3	.43	-3.94***	1.47	-7.49*	3.99	-6.40**	2.81			
4	.52	-3.63**	1.51	-7.58***	4.02	-6.61**	2.99			
5	.59	-3.97***	1.23	-9.98*	4.78	-5.80**	2.55			
6	.66	-4.06***	1.10	-9.36**	4.26	-6.01***	2.29			
7	.73	-4.96***	1.10	-11.41**	4.76	-7.37***	2.38			
8	.80	-4.56***	1.23	-9.83**	4.41	-7.74***	2.93			
9	.87	-4.25***	1.58	-9.53**	4.80	-7.56**	3.48			
10	.94	-5.32***	1.19	-11.27*	4.58	-8.74***	2.82			
11	1.01	-5.63***	1.30	-11.05**	4.47	-9.32***	2.85			
12	1.11	-5.53***	1.39	-10.39**	4.24	-9.67***	3.11			
13	1.21	-5.93***	1.31	-11.68**	4.33	-10.09***	2.45			
14	1.32	-5.81***	1.30	-12.24***	4.56	-9.95***	2.75			
15	1.45	-6.84***	1.58	-12.72***	4.42	-11.46***	2.89			
16	1.60	-6.60***	1.62	-13.38***	5.02	-12.31***	3.52			
17	1.79	-7.22***	1.57	-15.44***	5.79	-12.66***	3.41			
18	2.07	-7.41***	1.76	-14.80***	5.53	-13.31***	3.78			
19	2.50	-7.52***	2.01	-14.70***	5.75	-14.10***	4.35			
20	3.57	-8.62***	2.15	-17.85**	6.66	-16.40***	4.56			
NYSE	1.22	-5.47***	1.30	-11.31***	4.53	-9.38***	2.86			

Table 2: Empirical responses of stock returns to monetary policy across NYSE liquidity portfolios (1994-2007 sample).
*** denotes significance at 1% level, ** significance at 5% level, * significance at 10% level.

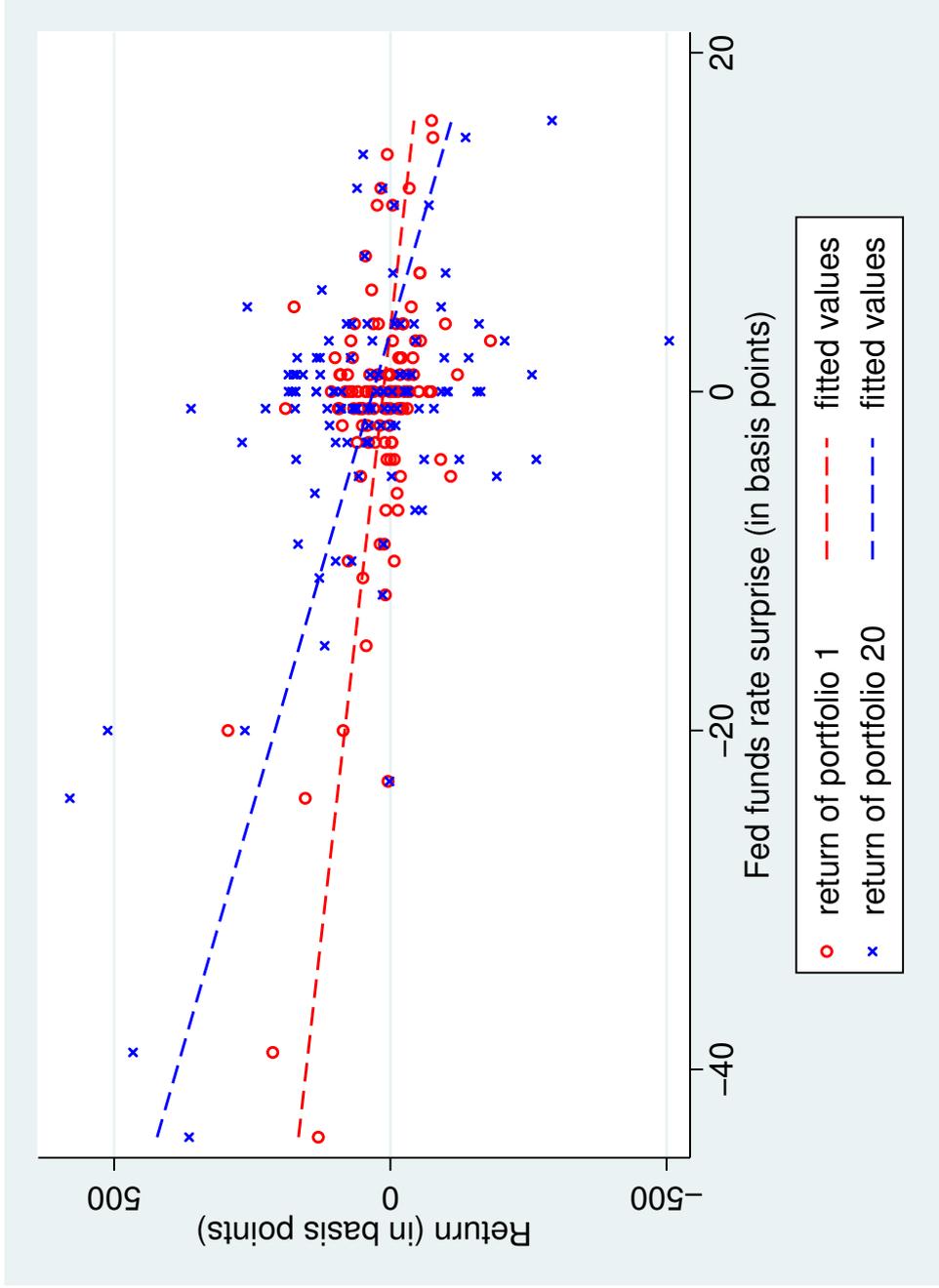


Figure 2: Unexpected component of the change in the policy rate on FOMC announcement dates and announcement-day NYSE stock returns for portfolio 1 (circles) and portfolio 20 (crosses).

Variable	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Δi_t	-5.37 (.11)	-5.56 (.11)	-5.60 (.13)	-5.83 (.12)	-5.82 (.13)	-5.21 (.099)	-5.23 (.098)	-5.30 (.110)	-5.30 (.112)
\mathcal{T}_t^s	2894 (148)	3094 (147)	2920 (181)	1256 (160)	589 (207)	4389 (315)	4454 (370)	2832 (333)	2190 (407)
$\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$		-553 (29)	-557 (30)	-492 (30)	-491 (32)	-554 (29)	-560 (31)	-485 (30)	-487 (32)
D_s			yes		yes		yes		yes
D_t				yes	yes			yes	yes
$(\Delta i_t)^2$						.04 (.008)	.04 (.008)	.05 (.009)	.05 (.010)
$(\mathcal{T}_t^s)^2$						-53852 (14751)	-57208 (15093)	-63775 (14887)	-56275 (15597)
R^2		.0241	.0286	.0778	.0778	.0290	.0290	.0783	.0784

Table 3: Effects of monetary policy on stock returns of individual NYSE stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (20). Number of observations: 205,760. Standard errors in parentheses. All estimates are significant at the 1 percent level.

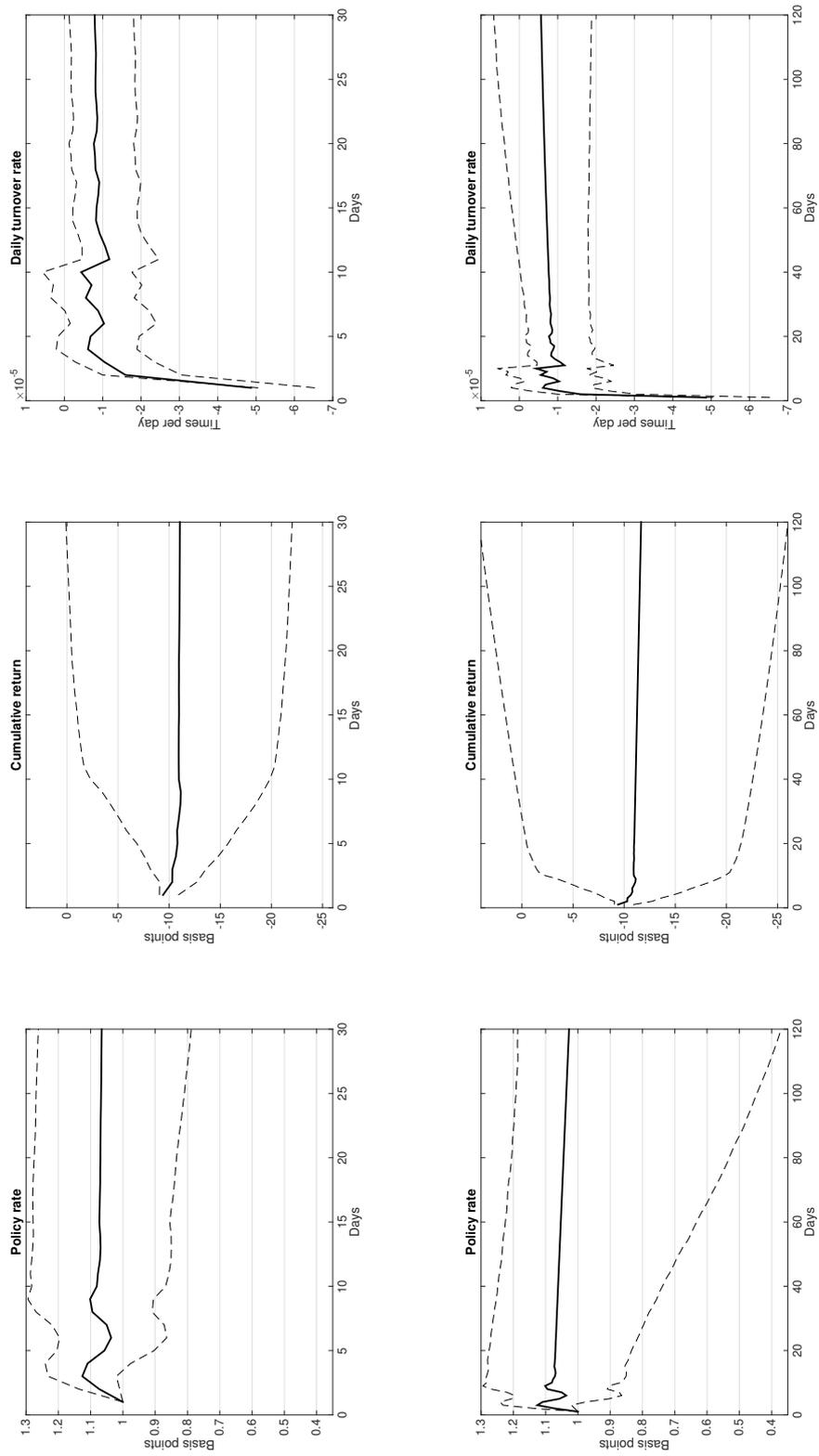


Figure 3: Empirical impulse responses to a 1 basis point increase in the policy rate. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

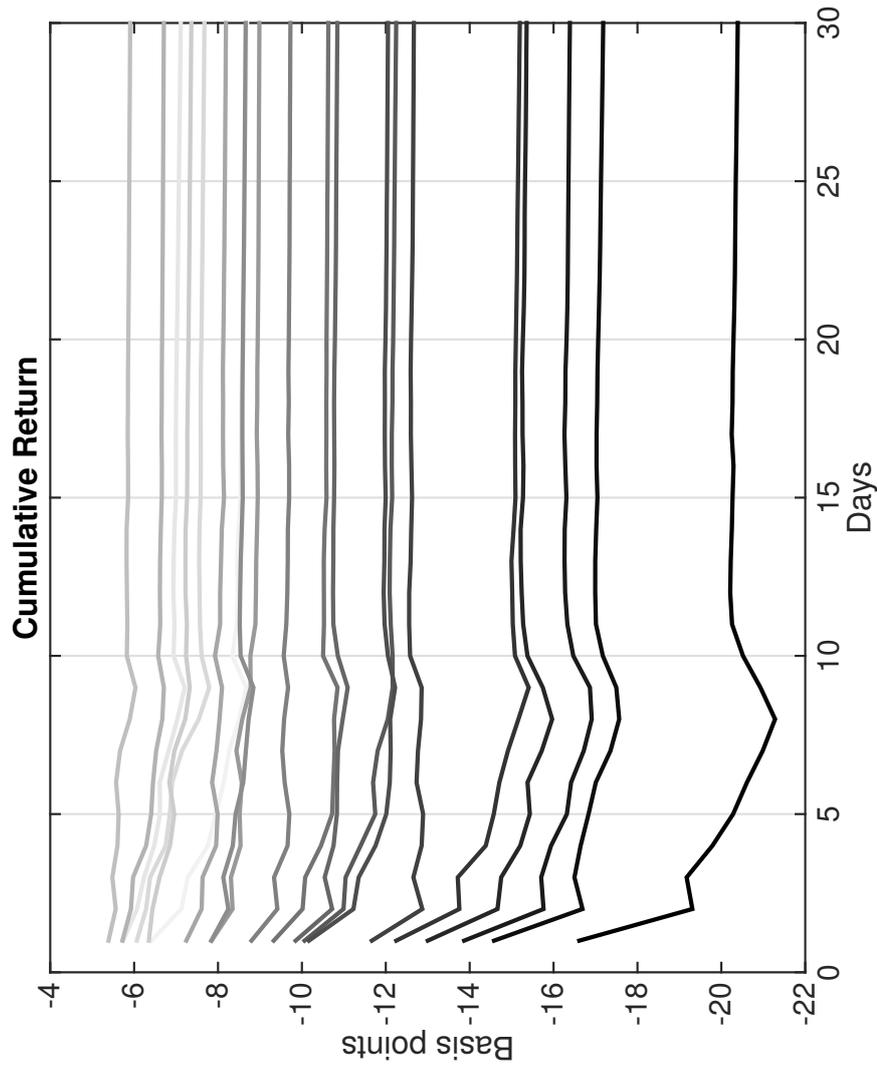


Figure 4: Empirical impulse responses of cumulative stock returns for the twenty NYSE liquidity portfolios to a 1 basis point increase in the policy rate (darker shades indicate more liquid portfolios).

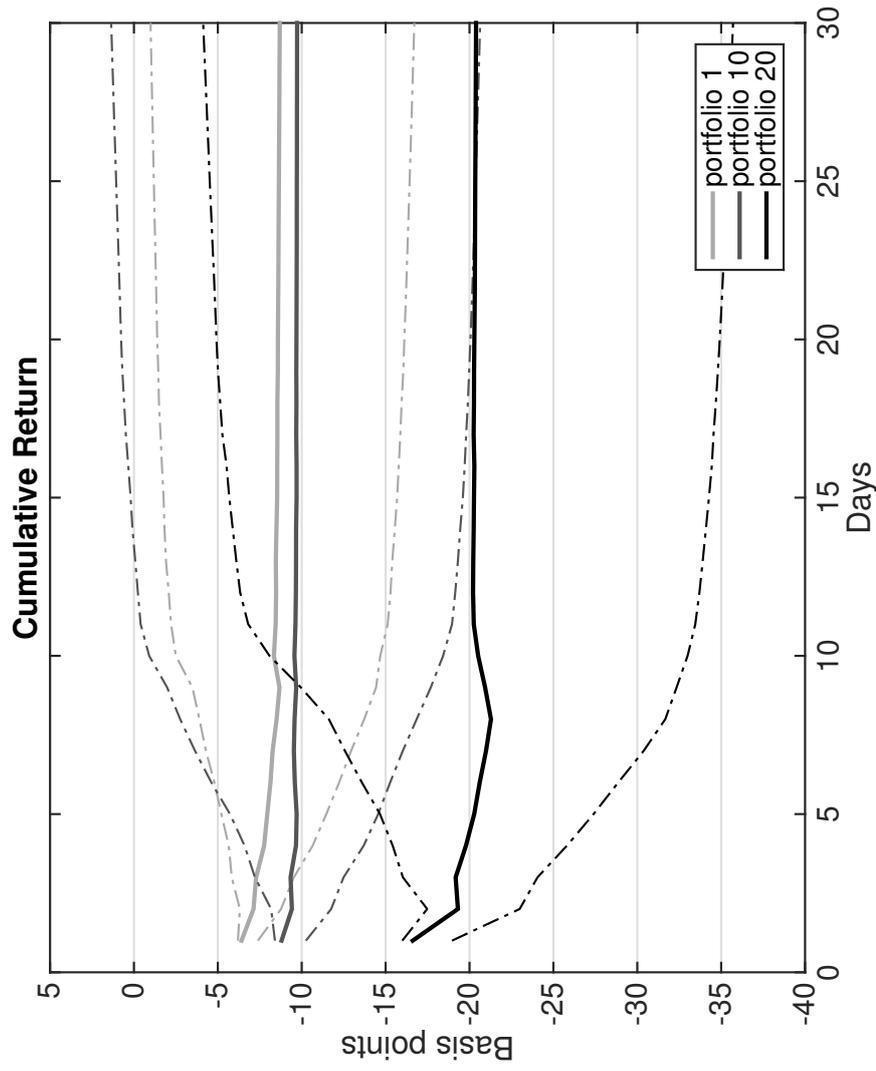


Figure 5: Empirical impulse responses of cumulative stock returns for selected NYSE liquidity portfolios to a 1 basis point increase in the policy rate. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

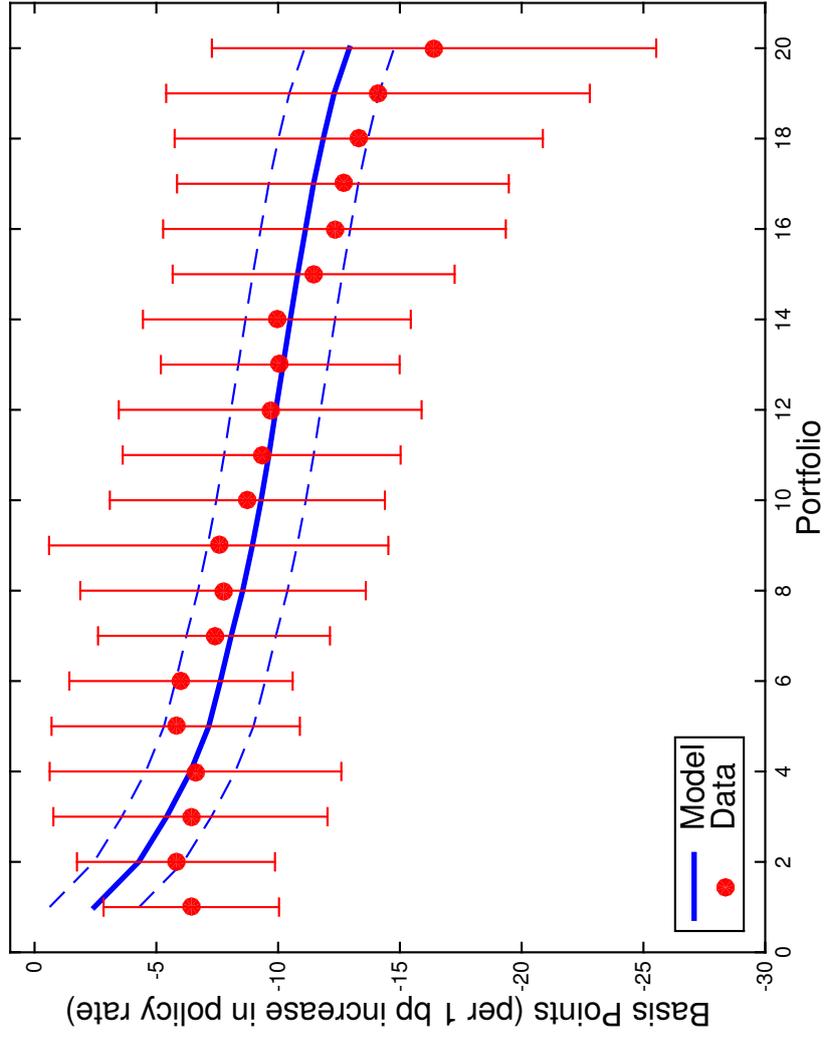


Figure 6: Cross-sectional announcement-day responses of stock returns to policy rate.

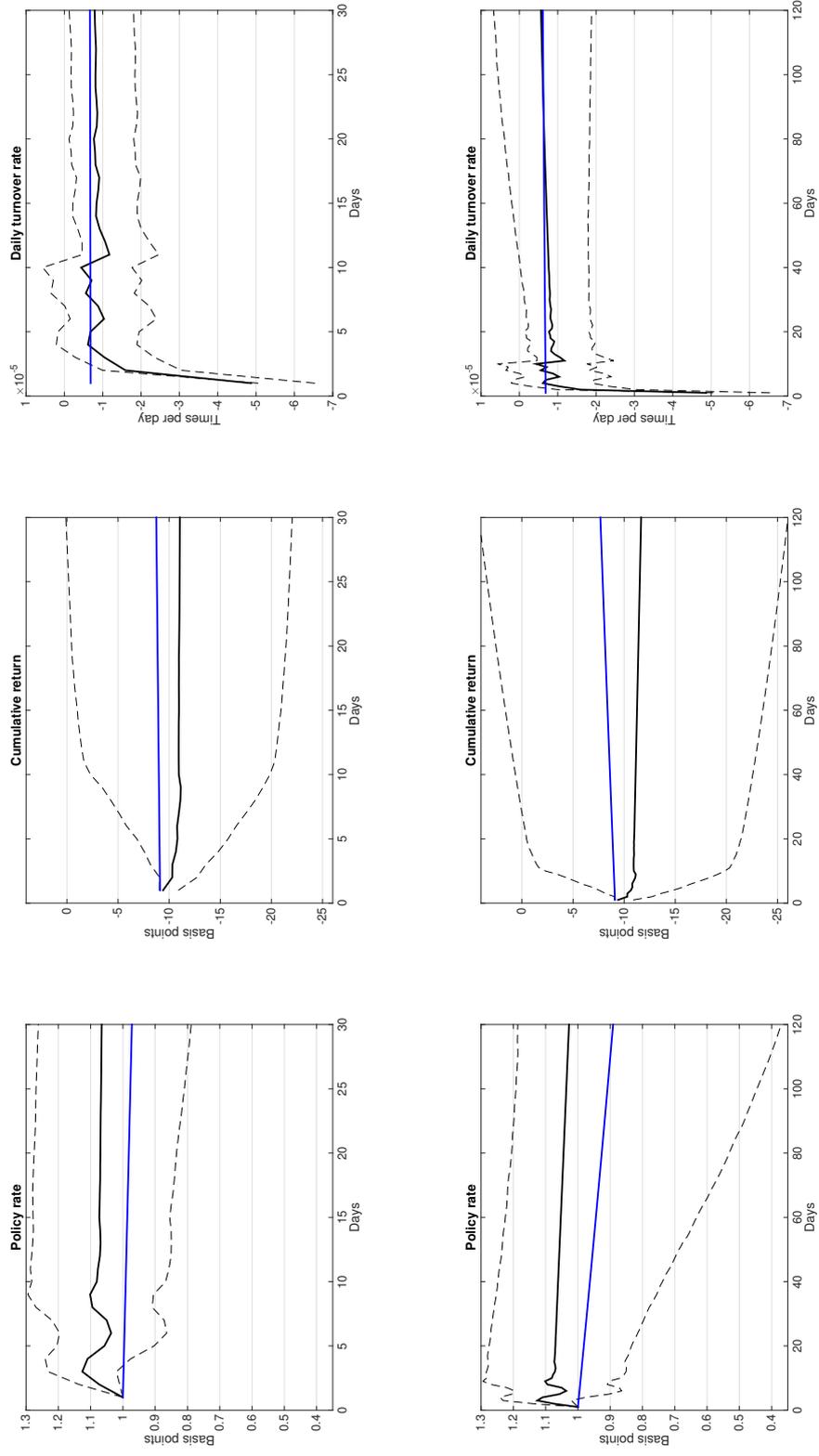


Figure 7: Empirical and theoretical impulse responses to a 1 basis point increase in the policy rate. Broken lines are 95 percent confidence intervals the empirical impulse response.

A Supplementary material: Proofs

A.1 Portfolio problems

Proof of Lemma 1. Notice that (3) implies

$$W_t^D(\mathbf{a}_t, k_t) = \phi_t \mathbf{a}_t + k_t + \bar{W}_t^D,$$

where

$$\bar{W}_t^D \equiv \max_{\tilde{\mathbf{a}}_{t+1} \in \mathbb{R}_+^2} [-\phi_t \tilde{\mathbf{a}}_{t+1} + \beta \mathbb{E}_t V_{t+1}^D(\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s)], \quad (27)$$

so (2) implies

$$\begin{aligned} \hat{W}_t^D(\mathbf{a}_t, k_t) &= k_t + \bar{W}_t^D + \max_{\hat{\mathbf{a}}_t \in \mathbb{R}_+^2} \phi_t \hat{\mathbf{a}}_t \\ \text{s.t. } \hat{a}_t^m + p_t \hat{a}_t^s &\leq a_t^m + p_t a_t^s. \end{aligned}$$

Hence,

$$\begin{aligned} \hat{a}_t^m(\mathbf{a}_t) &\begin{cases} = a_t^m + p_t a_t^s & \text{if } 0 < \varepsilon_t^* \\ \in [0, a_t^m + p_t a_t^s] & \text{if } 0 = \varepsilon_t^* \\ = 0 & \text{if } \varepsilon_t^* < 0, \end{cases} \\ \hat{a}_t^s(\mathbf{a}_t) &= (1/p_t) [a_t^m + p_t a_t^s - \hat{a}_t^m(\mathbf{a}_t)], \end{aligned}$$

and

$$\hat{W}_t^D(\mathbf{a}_t, k_t) = \max(\phi_t^m, \phi_t^s/p_t) (a_t^m + p_t a_t^s) + k_t + \bar{W}_t^D. \quad (28)$$

Also, notice that (4) implies

$$W_t^I(\mathbf{a}_t, k_t) = \phi_t \mathbf{a}_t - k_t + \bar{W}_t^I, \quad (29)$$

where

$$\bar{W}_t^I \equiv T_t + \max_{\tilde{\mathbf{a}}_{t+1} \in \mathbb{R}_+^2} \left[-\phi_t \tilde{\mathbf{a}}_{t+1} + \beta \mathbb{E}_t \int V_{t+1}^I [\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s + (1-\delta) A^s, \varepsilon] dG(\varepsilon) \right]. \quad (30)$$

With (28) and (29), (1) can be written as

$$\begin{aligned} \max_{\bar{a}_t^m, k_t} &\left[(\varepsilon_t^* - \varepsilon) (\bar{a}_t^m - a_{it}^m) \frac{1}{p_t} y_t - k_t \right]^\theta k_t^{1-\theta} \\ \text{s.t. } &0 \leq k_t \leq (\varepsilon_t^* - \varepsilon) (\bar{a}_t^m - a_{it}^m) \frac{1}{p_t} y_t \end{aligned}$$

with $\bar{a}_t^s = a_{it}^s + (1/p_t)(a_{it}^m - \bar{a}_t^m)$. Hence,

$$\bar{a}_t^m(\mathbf{a}_{it}, \varepsilon) \begin{cases} = a_{it}^m + p_t a_{it}^s & \text{if } \varepsilon < \varepsilon_t^* \\ \in [0, a_{it}^m + p_t a_{it}^s] & \text{if } \varepsilon = \varepsilon_t^* \\ = 0 & \text{if } \varepsilon_t^* < \varepsilon, \end{cases}$$

$$\bar{a}_t^s(\mathbf{a}_{it}, \varepsilon) = a_{it}^s + (1/p_t)[a_{it}^m - \bar{a}_t^m(\mathbf{a}_{it}, \varepsilon)],$$

and

$$k_t(\mathbf{a}_{it}, \varepsilon) = (1 - \theta)(\varepsilon - \varepsilon_t^*) \left[\mathbb{I}_{\{\varepsilon_t^* < \varepsilon\}} \frac{1}{p_t} a_{it}^m - \mathbb{I}_{\{\varepsilon < \varepsilon_t^*\}} a_{it}^s \right] y_t.$$

This concludes the proof. ■

Lemma 2 *Let $(\tilde{a}_{dt+1}^m, \tilde{a}_{dt+1}^s)$ and $(\tilde{a}_{it+1}^m, \tilde{a}_{it+1}^s)$ denote the portfolios chosen by a dealer and an investor, respectively, in the second subperiod of period t . These portfolios must satisfy the following first-order necessary and sufficient conditions:*

$$\phi_t^m \geq \beta \mathbb{E}_t \max(\phi_{t+1}^m, \phi_{t+1}^s/p_{t+1}), \text{ with “} = \text{” if } \tilde{a}_{dt+1}^m > 0 \quad (31)$$

$$\phi_t^s \geq \beta \delta \mathbb{E}_t \max(p_{t+1} \phi_{t+1}^m, \phi_{t+1}^s), \text{ with “} = \text{” if } \tilde{a}_{dt+1}^s > 0 \quad (32)$$

$$\phi_t^m \geq \beta \mathbb{E}_t \left[\phi_{t+1}^m + \alpha \theta \int_{\varepsilon_{t+1}^*}^{\varepsilon_H} (\varepsilon - \varepsilon_{t+1}^*) y_{t+1} dG(\varepsilon) \frac{1}{p_{t+1}} \right], \text{ with “} = \text{” if } \tilde{a}_{it+1}^m > 0 \quad (33)$$

$$\phi_t^s \geq \beta \delta \mathbb{E}_t \left[\bar{\varepsilon} y_{t+1} + \phi_{t+1}^s + \alpha \theta \int_{\varepsilon_L}^{\varepsilon_{t+1}^*} (\varepsilon_{t+1}^* - \varepsilon) y_{t+1} dG(\varepsilon) \right], \text{ with “} = \text{” if } \tilde{a}_{it+1}^s > 0. \quad (34)$$

Proof. With Lemma 1, we can write $V_t^I(\mathbf{a}_t, \varepsilon)$ as

$$V_t^I(\mathbf{a}_t, \varepsilon) = \left[\alpha \theta (\varepsilon - \varepsilon_t^*) \mathbb{I}_{\{\varepsilon_t^* < \varepsilon\}} \frac{1}{p_t} y_t + \phi_t^m \right] a_t^m + \left\{ \left[\varepsilon + \alpha \theta (\varepsilon_t^* - \varepsilon) \mathbb{I}_{\{\varepsilon < \varepsilon_t^*\}} \right] y_t + \phi_t^s \right\} a_t^s + \bar{W}_t^I \quad (35)$$

and $V_t^D(\mathbf{a}_t)$ as

$$V_t^D(\mathbf{a}_t) = \alpha \int k_t(\mathbf{a}_{it}, \varepsilon) dH_{It}(\mathbf{a}_{it}, \varepsilon) + \max(\phi_t^m, \phi_t^s/p_t)(a_t^m + p_t a_t^s) + \bar{W}_t^D.$$

Since ε is i.i.d. over time, the portfolio that each investor chooses to carry into period $t + 1$ is independent of ε . Therefore, we can write $dH_{It}(\mathbf{a}_t, \varepsilon) = dF_{It}(\mathbf{a}_t) dG(\varepsilon)$, where F_{It} is the joint cumulative distribution function of investors' money and equity holdings at the beginning of the OTC round of period t . Thus,

$$V_t^D(\mathbf{a}_t) = \max(\phi_t^m, \phi_t^s/p_t)(a_t^m + p_t a_t^s) + V_t^D(\mathbf{0}), \quad (36)$$

where

$$V_t^D(\mathbf{0}) = \alpha(1 - \theta) \int (\varepsilon - \varepsilon_t^*) \left[\mathbb{I}_{\{\varepsilon_t^* < \varepsilon\}} \frac{1}{p_t} A_{It}^m - \mathbb{I}_{\{\varepsilon < \varepsilon_t^*\}} A_{It}^s \right] dG(\varepsilon) y_t + \bar{W}_t^D.$$

From (36) we have

$$V_{t+1}^D(\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s) = \max(\phi_{t+1}^m, \phi_{t+1}^s/p_{t+1}) (\tilde{a}_{t+1}^m + p_{t+1} \delta \tilde{a}_{t+1}^s) + V_{t+1}^D(\mathbf{0}),$$

and from (35) we have

$$\begin{aligned} & \int V_{t+1}^I[\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s + (1 - \delta) A^s, \varepsilon] dG(\varepsilon) \\ &= \left[\alpha \theta \int_{\varepsilon_{t+1}^*}^{\varepsilon_H} (\varepsilon - \varepsilon_{t+1}^*) dG(\varepsilon) \frac{1}{p_{t+1}} y_{t+1} + \phi_{t+1}^m \right] \tilde{a}_{t+1}^m \\ &+ \delta \left\{ \left[\bar{\varepsilon} + \int_{\varepsilon_L}^{\varepsilon_{t+1}^*} \alpha \theta (\varepsilon_{t+1}^* - \varepsilon) dG(\varepsilon) \right] y_{t+1} + \phi_{t+1}^s \right\} \tilde{a}_{t+1}^s + \zeta_{t+1}, \end{aligned}$$

where $\zeta_{t+1} \equiv \left\{ \left[\bar{\varepsilon} + \alpha \theta \int (\varepsilon_{t+1}^* - \varepsilon) \mathbb{I}_{\{\varepsilon < \varepsilon_{t+1}^*\}} dG(\varepsilon) \right] y_{t+1} + \phi_{t+1}^s \right\} (1 - \delta) A^s + \bar{W}_{t+1}^I$. Thus, the necessary and sufficient first-order conditions corresponding to the maximization problems in (27) and (30) are as in the statement of the lemma. ■

A.2 Market clearing in the OTC market

Lemma 3 *In period t , the interdealer market-clearing condition for equity is*

$$\{\alpha [1 - G(\varepsilon_t^*)] A_{It}^m + \chi(\varepsilon_t^*, 0) A_{Dt}^m\} \frac{1}{p_t} = \alpha G(\varepsilon_t^*) A_{It}^s + [1 - \chi(\varepsilon_t^*, 0)] A_{Dt}^s. \quad (37)$$

Proof. Recall $\bar{A}_{Dt}^s = \int \hat{a}_t^s(\mathbf{a}_t) dF_{Dt}(\mathbf{a}_t)$, so from Lemma 1, we have

$$\bar{A}_{Dt}^s = \chi(\varepsilon_t^*, 0) (A_{Dt}^s + A_{Dt}^m/p_t).$$

Similarly, $\bar{A}_{It}^s = \alpha \int \bar{a}_t^s(\mathbf{a}_t, \varepsilon) dH_{It}(\mathbf{a}_t, \varepsilon)$, so from Lemma 1, we have

$$\bar{A}_{It}^s = \alpha [1 - G(\varepsilon_t^*)] (A_{It}^s + A_{It}^m/p_t).$$

With these expressions, the market-clearing condition for equity in the interdealer market of period t , i.e., $\bar{A}_{Dt}^s + \bar{A}_{It}^s = A_{Dt}^s + \alpha A_{It}^s$, can be written as in the statement of the lemma. ■

A.3 Equilibrium characterization

Corollary 2 *A sequence of prices, $\{1/p_t, \phi_t^m, \phi_t^s\}_{t=0}^\infty$, together with bilateral terms of trade in the OTC market, $\{\bar{\mathbf{a}}_t, k_t\}_{t=0}^\infty$, dealer portfolios, $\{\langle \hat{\mathbf{a}}_{dt}, \bar{\mathbf{a}}_{dt+1}, \mathbf{a}_{dt+1} \rangle_{d \in \mathcal{D}}\}_{t=0}^\infty$, and investor portfolios, $\{\langle \tilde{\mathbf{a}}_{it+1}, \mathbf{a}_{it+1} \rangle_{i \in \mathcal{I}}\}_{t=0}^\infty$, constitute an equilibrium if and only if they satisfy the following conditions for all t :*

(i) *Intermediation fee and optimal post-trade portfolios in OTC market*

$$\begin{aligned} k_t(\mathbf{a}_t, \varepsilon) &= (1 - \theta) (\varepsilon - \varepsilon_t^*) \left[\chi(\varepsilon_t^*, \varepsilon) \frac{1}{p_t} a_t^m - [1 - \chi(\varepsilon_t^*, \varepsilon)] a_t^s \right] y_t \\ \bar{a}_t^m(\mathbf{a}_t, \varepsilon) &= [1 - \chi(\varepsilon_t^*, \varepsilon)] (a_t^m + p_t a_t^s) \\ \bar{a}_t^s(\mathbf{a}_t, \varepsilon) &= \chi(\varepsilon_t^*, \varepsilon) (1/p_t) (a_t^m + p_t a_t^s) \\ \hat{\mathbf{a}}_t(\mathbf{a}_t) &= \bar{\mathbf{a}}_t(\mathbf{a}_t, 0). \end{aligned}$$

(ii) *Interdealer market clearing*

$$\{\alpha [1 - G(\varepsilon^*)] A_{I_t}^m + \chi(\varepsilon_t^*, 0) A_{D_t}^m\} \frac{1}{p_t} = \alpha G(\varepsilon^*) A_{I_t}^s + [1 - \chi(\varepsilon_t^*, 0)] A_{D_t}^s,$$

where $A_{j_t}^m \equiv \int a_t^m dF_{j_t}(\mathbf{a}_t)$ and $A_{j_t}^s \equiv \int a_t^s dF_{j_t}(\mathbf{a}_t)$ for $j \in \{D, I\}$.

(iii) *Optimal end-of-period portfolios:*

$$\begin{aligned} \phi_t^m &\geq \beta \mathbb{E}_t \max(\phi_{t+1}^m, \phi_{t+1}^s / p_{t+1}) \\ \phi_t^s &\geq \beta \delta \mathbb{E}_t \max(p_{t+1} \phi_{t+1}^m, \phi_{t+1}^s) \\ \phi_t^m &\geq \beta \mathbb{E}_t \left[\phi_{t+1}^m + \alpha \theta \int_{\varepsilon_{t+1}^*}^{\varepsilon^H} (\varepsilon - \varepsilon_{t+1}^*) dG(\varepsilon) \frac{1}{p_{t+1}} y_{t+1} \right] \\ \phi_t^s &\geq \beta \delta \mathbb{E}_t \left[\bar{\varepsilon} y_{t+1} + \phi_{t+1}^s + \alpha \theta \int_{\varepsilon_L}^{\varepsilon_{t+1}^*} (\varepsilon_{t+1}^* - \varepsilon) y_{t+1} dG(\varepsilon) \right] \end{aligned}$$

with

$$\begin{aligned} &[\phi_t^m - \beta \mathbb{E}_t \max(\phi_{t+1}^m, \phi_{t+1}^s / p_{t+1})] \tilde{a}_{dt+1}^m = 0 \\ &[\phi_t^s - \beta \delta \mathbb{E}_t \max(p_{t+1} \phi_{t+1}^m, \phi_{t+1}^s)] \tilde{a}_{dt+1}^s = 0 \\ &\left\{ \phi_t^m - \beta \mathbb{E}_t \left[\phi_{t+1}^m + \alpha \theta \int_{\varepsilon_{t+1}^*}^{\varepsilon^H} (\varepsilon - \varepsilon_{t+1}^*) dG(\varepsilon) \frac{1}{p_{t+1}} y_{t+1} \right] \right\} \tilde{a}_{it+1}^m = 0 \\ &\left\{ \phi_t^s - \beta \delta \mathbb{E}_t \left[\bar{\varepsilon} y_{t+1} + \phi_{t+1}^s + \alpha \theta \int_{\varepsilon_L}^{\varepsilon_{t+1}^*} (\varepsilon_{t+1}^* - \varepsilon) y_{t+1} dG(\varepsilon) \right] \right\} \tilde{a}_{it+1}^s = 0 \end{aligned}$$

for all $d \in \mathcal{D}$ and all $i \in \mathcal{I}$, and

$$\begin{aligned} a_{jt+1}^m &= \tilde{a}_{jt+1}^m \\ a_{jt+1}^s &= \delta \tilde{a}_{jt+1}^s + \mathbb{I}_{\{j \in \mathcal{I}\}} (1 - \delta) A^s \\ \tilde{a}_{jt+1}^k &\in \mathbb{R}_+ \text{ for } k \in \{s, m\} \end{aligned}$$

for all $j \in \mathcal{D} \cup \mathcal{I}$.

(iv) End-of-period market clearing

$$\begin{aligned} \tilde{A}_{Dt+1}^s + \tilde{A}_{It+1}^s &= A^s \\ \tilde{A}_{Dt+1}^m + \tilde{A}_{It+1}^m &= A_{t+1}^m, \end{aligned}$$

where $\tilde{A}_{Dt+1}^k \equiv \int_{\mathcal{D}} \tilde{a}_{xt+1}^k dx$ and $\tilde{A}_{It+1}^k \equiv \int_{\mathcal{I}} \tilde{a}_{xt+1}^k dx$ for $k \in \{s, m\}$.

Proof. Follows immediately from Definition 1 together with Lemma 1, Lemma 2, and Lemma 3. ■

Lemma 4 Consider $\hat{\mu}$ and $\bar{\mu}$ as defined in (5). Then $\hat{\mu} < \bar{\mu}$.

Proof of Lemma 4. Define $\Upsilon(\zeta) : \mathbb{R} \rightarrow \mathbb{R}$ by $\Upsilon(\zeta) \equiv \bar{\beta} [1 + \alpha\theta(1 - \bar{\beta}\delta)\zeta]$. Let $\hat{\zeta} \equiv \frac{(1-\alpha\theta)(\bar{\varepsilon}-\bar{\varepsilon})}{\alpha\theta\bar{\varepsilon}}$ and $\bar{\zeta} \equiv \frac{\bar{\varepsilon}-\varepsilon_L}{\bar{\beta}\delta\bar{\varepsilon}+(1-\bar{\beta}\delta)\varepsilon_L}$, so that $\hat{\mu} = \Upsilon(\hat{\zeta})$ and $\bar{\mu} = \Upsilon(\bar{\zeta})$. Since Υ is strictly increasing, $\hat{\mu} < \bar{\mu}$ if and only if $\hat{\zeta} < \bar{\zeta}$. With (6) and the fact that $\bar{\varepsilon} \equiv \int_{\varepsilon_L}^{\varepsilon_H} \varepsilon dG(\varepsilon) = \varepsilon_H - \int_{\varepsilon_L}^{\varepsilon_H} G(\varepsilon) d\varepsilon$,

$$\hat{\zeta} = \frac{\int_{\hat{\varepsilon}}^{\varepsilon_H} [1 - G(\varepsilon)] d\varepsilon}{\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\hat{\varepsilon}} G(\varepsilon) d\varepsilon},$$

so clearly,

$$\hat{\zeta} < \frac{\int_{\varepsilon_L}^{\varepsilon_H} [1 - G(\varepsilon)] d\varepsilon}{\bar{\varepsilon}} = \frac{\bar{\varepsilon} - \varepsilon_L}{\bar{\varepsilon}} < \bar{\zeta}.$$

Hence, $\hat{\mu} < \bar{\mu}$. ■

Proof of Proposition 1. In an equilibrium with no money (or no valued money), there is no trade in the OTC market. From Lemma 2, the first-order conditions for a dealer $d \in \mathcal{D}$ and an investor $i \in \mathcal{I}$ in the time t Walrasian market are

$$\begin{aligned} \phi_t^s &\geq \beta\delta\mathbb{E}_t\phi_{t+1}^s, \text{ “} = \text{” if } \tilde{a}_{t+1d}^s > 0 \\ \phi_t^s &\geq \beta\delta\mathbb{E}_t(\bar{\varepsilon}y_{t+1} + \phi_{t+1}^s), \text{ “} = \text{” if } \tilde{a}_{t+1i}^s > 0. \end{aligned}$$

In a recursive equilibrium, $\mathbb{E}_t(\phi_{t+1}^s/\phi_t^s) = \bar{\gamma}$, and $\beta\delta\bar{\gamma} < 1$ is a maintained assumption, so no dealer holds equity. The Walrasian market for equity can only clear if $\phi^s = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\bar{\varepsilon}$. This establishes parts (i) and (iii) in the statement of the proposition.

Next, we turn to monetary equilibria. In a recursive equilibrium, the Euler equations (31)-(34) become

$$\mu \geq \bar{\beta}, \text{ " = " if } \tilde{a}_{dt+1}^m > 0 \quad (38)$$

$$\phi^s \geq \bar{\beta}\delta\bar{\phi}^s, \text{ " = " if } \tilde{a}_{dt+1}^s > 0 \quad (39)$$

$$1 \geq \frac{\bar{\beta}}{\mu} \left[1 + \frac{\alpha\theta}{\varepsilon^* + \phi^s} \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon) \right], \text{ " = " if } \tilde{a}_{it+1}^m > 0 \quad (40)$$

$$\phi^s \geq \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right], \text{ " = " if } \tilde{a}_{it+1}^s > 0. \quad (41)$$

(We have used the fact that, as will become clear below, $\bar{\phi}^s \equiv \varepsilon^* + \phi^s \geq \varepsilon_L + \phi^s > \phi^s$ in any equilibrium.) Under our maintained assumption $\bar{\beta} < \mu$, (38) implies $\tilde{a}_{dt+1}^m = Z_D = 0$, so (40) must hold with equality for some investor in a monetary equilibrium. Thus, in order to find a monetary equilibrium, there are three possible equilibrium configurations to consider depending on the binding patterns of the complementary slackness conditions associated with (39) and (41). The interdealer market-clearing condition, $\bar{A}_{Dt}^s + \bar{A}_{It}^s = A_{Dt}^s + \alpha A_{It}^s$, must hold for all three configurations. Lemma 3 shows that this condition is equivalent to (37) and in a recursive equilibrium (37) reduces to

$$Z = \frac{\varepsilon^* + \phi^s}{\alpha [1 - G(\varepsilon^*)]} \{ \alpha G(\varepsilon^*) A_I^s + [1 - \chi(\varepsilon^*, 0)] A_D^s \}.$$

This condition in turn reduces to (12) if, as shown below, the equilibrium has $0 < \varepsilon^*$. The rest of the proof proceeds in three steps.

Step 1: Try to construct a recursive monetary equilibrium with $\tilde{a}_{dt+1}^s = 0$ for all $d \in \mathcal{D}$ and $\tilde{a}_{it+1}^s > 0$ for some $i \in \mathcal{I}$. The equilibrium conditions for this case are (12) together with

$$\phi^s > \bar{\beta}\delta\bar{\phi}^s \quad (42)$$

$$1 = \frac{\bar{\beta}}{\mu} \left[1 + \frac{\alpha\theta}{\varepsilon^* + \phi^s} \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon) \right] \quad (43)$$

$$\phi^s = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] \quad (44)$$

and

$$\tilde{a}_{dt+1}^m = 0 \text{ for all } d \in \mathcal{D} \quad (45)$$

$$\tilde{a}_{it+1}^m \geq 0, \text{ with “} > \text{” for some } i \in \mathcal{I} \quad (46)$$

$$\tilde{a}_{dt+1}^s = 0 \text{ for all } d \in \mathcal{D} \quad (47)$$

$$\tilde{a}_{it+1}^s \geq 0, \text{ with “} > \text{” for some } i \in \mathcal{I}. \quad (48)$$

Conditions (43) and (44) are to be solved for the two unknowns ε^* and ϕ^s . Substitute (44) into (43) to obtain

$$1 = \frac{\bar{\beta}}{\mu} \left[1 + \alpha\theta \frac{\int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon)}{\varepsilon^* + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right]} \right], \quad (49)$$

which is a single equation in ε^* . Define

$$T(x) \equiv \frac{\int_x^{\varepsilon_H} (\varepsilon - x) dG(\varepsilon)}{\frac{1}{1-\bar{\beta}\delta}x + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\hat{T}(x)} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} \quad (50)$$

with

$$\hat{T}(x) \equiv \bar{\varepsilon} - x + \alpha\theta \int_{\varepsilon_L}^x (x - \varepsilon) dG(\varepsilon), \quad (51)$$

and notice that ε^* solves (49) if and only if it satisfies $T(\varepsilon^*) = 0$. T is a continuous real-valued function on $[\varepsilon_L, \varepsilon_H]$, with

$$T(\varepsilon_L) = \frac{\bar{\varepsilon} - \varepsilon_L}{\varepsilon_L + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\bar{\varepsilon}} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta},$$

$$T(\varepsilon_H) = -\frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} < 0,$$

and

$$T'(x) = -\frac{[1-G(x)]\left\{x + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^x G(\varepsilon)d\varepsilon\right]\right\} + \left[\int_x^{\varepsilon_H} [1-G(\varepsilon)]d\varepsilon\right]\left\{1 + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\alpha\theta G(x)\right\}}{\left\{x + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^x G(\varepsilon)d\varepsilon\right]\right\}^2} < 0.$$

Hence, if $T(\varepsilon_L) > 0$, or equivalently, if $\mu < \bar{\mu}$ (with $\bar{\mu}$ is as defined in (5)), then there exists a unique $\varepsilon^* \in (\varepsilon_L, \varepsilon_H)$ that satisfies $T(\varepsilon^*) = 0$ (and $\varepsilon^* \downarrow \varepsilon_L$ as $\mu \uparrow \bar{\mu}$). Once we know ε^* , ϕ^s is given by (44). Given ε^* and ϕ^s , the values of Z , $\bar{\phi}^s$, ϕ_t^m , and p_t are obtained using (12) (with $A_I^s = A^s$ and $A_D^s = 0$), (9), (10), and (11). To conclude this step, notice that for this case to be an equilibrium, (42) must hold, or equivalently, using $\bar{\phi}^s = \varepsilon^* + \phi^s$ and (44), it must be that $\hat{T}(\varepsilon^*) > 0$, where \hat{T} is the continuous function on $[\varepsilon_L, \varepsilon_H]$ defined in (51). Notice that

$\hat{T}'(x) = -[1 - \alpha\theta G(x)] < 0$, and $\hat{T}(\varepsilon_H) = -(1 - \alpha\theta)(\varepsilon_H - \bar{\varepsilon}) < 0 < \bar{\varepsilon} - \varepsilon_L = \hat{T}(\varepsilon_L)$, so there exists a unique $\hat{\varepsilon} \in (\varepsilon_L, \varepsilon_H)$ such that $\hat{T}(\hat{\varepsilon}) = 0$. (Since $\hat{T}(\bar{\varepsilon}) > 0$, and $\hat{T}' < 0$, it follows that $\bar{\varepsilon} < \hat{\varepsilon}$.) Then $\hat{T}'(x) < 0$ implies $\hat{T}(\varepsilon^*) \geq 0$ if and only if $\varepsilon^* \leq \hat{\varepsilon}$, with “=” for $\varepsilon^* = \hat{\varepsilon}$. With (50), we know that $\varepsilon^* < \hat{\varepsilon}$ if and only if $T(\hat{\varepsilon}) < 0 = T(\varepsilon^*)$, i.e., if and only if

$$\bar{\beta} \left[1 + \frac{(1 - \bar{\beta}\delta) \alpha\theta \int_{\hat{\varepsilon}}^{\varepsilon_H} (\varepsilon - \hat{\varepsilon}) dG(\varepsilon)}{\hat{\varepsilon}} \right] < \mu.$$

Since $\hat{T}(\hat{\varepsilon}) = -(1 - \alpha\theta)(\hat{\varepsilon} - \bar{\varepsilon}) + \alpha\theta \int_{\hat{\varepsilon}}^{\varepsilon_H} (\varepsilon - \hat{\varepsilon}) dG(\varepsilon) = 0$, this last condition is equivalent to $\hat{\mu} < \mu$, where $\hat{\mu}$ is as defined in (5). The allocations and asset prices described in this step correspond to those in the statement of the proposition for $\mu \in (\hat{\mu}, \bar{\mu})$.

Step 2: Try to construct a recursive monetary equilibrium with $a_{dt+1}^s > 0$ for some $d \in \mathcal{D}$ and $a_{it+1}^s = 0$ for all $i \in \mathcal{I}$. The equilibrium conditions are (12), (43), (45), and (46), together with

$$\phi^s = \bar{\beta}\delta\bar{\phi}^s \tag{52}$$

$$\phi^s > \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right], \text{ “=” if } \tilde{a}_{it+1}^s > 0. \tag{53}$$

$$\tilde{a}_{dt+1}^s \geq 0, \text{ with “>” for some } d \in \mathcal{D} \tag{54}$$

$$\tilde{a}_{it+1}^s = 0, \text{ for all } i \in \mathcal{I}. \tag{55}$$

The conditions (43) and (52) are to be solved for ε^* and ϕ^s . First use $\bar{\phi}^s = \varepsilon^* + \phi^s$ in (52) to obtain

$$\phi^s = \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \varepsilon^*. \tag{56}$$

Substitute (56) in (43) to obtain

$$1 = \frac{\bar{\beta}}{\mu} \left[1 + \frac{\alpha\theta(1 - \bar{\beta}\delta) \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon)}{\varepsilon^*} \right], \tag{57}$$

which is a single equation in ε^* . Define

$$R(x) \equiv \frac{(1 - \bar{\beta}\delta) \int_x^{\varepsilon_H} (\varepsilon - x) dG(\varepsilon)}{x} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} \tag{58}$$

and notice that ε^* solves (57) if and only if it satisfies $R(\varepsilon^*) = 0$. R is a continuous real-valued function on $[\varepsilon_L, \varepsilon_H]$, with

$$R(\varepsilon_L) = \frac{(1 - \bar{\beta}\delta)(\bar{\varepsilon} - \varepsilon_L)}{\varepsilon_L} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta}$$

$$R(\varepsilon_H) = -\frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta}$$

and

$$R'(x) = -\frac{[1 - G(x)]x + \int_x^{\varepsilon_H} [1 - G(\varepsilon)] d\varepsilon}{\frac{1}{1 - \bar{\beta}\delta}x^2} < 0.$$

Hence, if $R(\varepsilon_L) > 0$, or equivalently, if

$$\mu < \bar{\beta} \left[1 + \frac{\alpha\theta(1 - \bar{\beta}\delta)(\bar{\varepsilon} - \varepsilon_L)}{\varepsilon_L} \right] \equiv \mu^o,$$

then there exists a unique $\varepsilon^* \in (\varepsilon_L, \varepsilon_H)$ that satisfies $R(\varepsilon^*) = 0$ (and $\varepsilon^* \downarrow \varepsilon_L$ as $\mu \uparrow \mu^o$). Having solved for ε^* , ϕ^s is obtained from (56). Given ε^* and ϕ^s , the values of Z , $\bar{\phi}^s$, ϕ_t^m , and p_t are obtained using (12) (with $A_D^s = A^s - A_I^s = \delta A^s$), (9), (10), and (11). Notice that for this case to be an equilibrium (53) must hold, or equivalently, using (56), it must be that $\hat{T}(\varepsilon^*) < 0$, which in turn is equivalent to $\hat{\varepsilon} < \varepsilon^*$. With (58), we know that $\hat{\varepsilon} < \varepsilon^*$ if and only if $R(\varepsilon^*) = 0 < R(\hat{\varepsilon})$, i.e., if and only if

$$\mu < \bar{\beta} \left[1 + \frac{\alpha\theta(1 - \bar{\beta}\delta) \int_{\hat{\varepsilon}}^{\varepsilon^*} (\varepsilon - \hat{\varepsilon}) dG(\varepsilon)}{\hat{\varepsilon}} \right],$$

which using $\hat{T}(\hat{\varepsilon}) = 0$ can be written as $\mu < \hat{\mu}$. To summarize, the prices and allocations constructed in this step constitute a recursive monetary equilibrium provided $\mu \in (\bar{\beta}, \min(\hat{\mu}, \mu^o))$. To conclude this step, we show that $\hat{\mu} < \bar{\mu} < \mu^o$, which together with the previous step will mean that there is no recursive monetary equilibrium for $\mu \geq \bar{\mu}$ (thus establishing part (ii) in the statement of the proposition). It is clear that $\bar{\mu} < \mu^o$, and we know that $\hat{\mu} < \bar{\mu}$ from Lemma 4. Therefore, the allocations and asset prices described in this step correspond to those in the statement of the proposition for the case with $\mu \in (\bar{\beta}, \min(\hat{\mu}, \mu^o)) = (\bar{\beta}, \hat{\mu})$.

Step 3: Try to construct a recursive monetary equilibrium with $\tilde{a}_{dt+1}^s > 0$ for some $d \in \mathcal{D}$ and $\tilde{a}_{it+1}^s > 0$ for some $i \in \mathcal{I}$. The equilibrium conditions are (12), (43), (44), (45), (46), and (52) with

$$\tilde{a}_{it+1}^s \geq 0 \text{ and } \tilde{a}_{dt+1}^s \geq 0, \text{ with " > " for some } i \in \mathcal{I} \text{ or some } d \in \mathcal{D}.$$

Notice that ε^* and ϕ^s are obtained as in Step 2. Now, however, (44) must also hold, which together with (56) implies we must have $\hat{T}(\varepsilon^*) = 0$, or equivalently, $\varepsilon^* = \hat{\varepsilon}$. In other words, this condition requires $R(\hat{\varepsilon}) = \hat{T}(\hat{\varepsilon})$, or equivalently, we must have $\mu = \hat{\mu}$. As before, the market-clearing condition (12) is used to obtain Z , while (9), (10), and (11) imply $\bar{\phi}^s$, ϕ_t^m , and p_t , respectively. The allocations and asset prices described in this step correspond to those in the statement of the proposition for the case with $\mu = \hat{\mu}$.

Combined, Steps 1, 2, and 3 prove part (iv) in the statement of the proposition. Part (v)(a) is immediate from (44) and (50), and part (v)(b) from (56) and (58). ■

Corollary 3 *The marginal valuation, ε^* , characterized in Proposition 1 is strictly decreasing in the rate of inflation, i.e., $\frac{\partial \varepsilon^*}{\partial \mu} < 0$ both for $\mu \in (\bar{\beta}, \hat{\mu})$ and for $\mu \in (\hat{\mu}, \bar{\mu})$.*

Proof. For $\mu \in (\bar{\beta}, \hat{\mu})$, implicitly differentiate $R(\varepsilon^*) = 0$ (with R given by (58)), and for $\mu \in (\hat{\mu}, \bar{\mu})$, implicitly differentiate $T(\varepsilon^*) = 0$ (with T given by (50)) to obtain

$$\frac{\partial \varepsilon^*}{\partial \mu} = \begin{cases} -\frac{\varepsilon^*}{\bar{\beta}\alpha\theta(1-\bar{\beta}\delta)[1-G(\varepsilon^*)]+\mu-\bar{\beta}} & \text{if } \bar{\beta} < \mu < \hat{\mu} \\ -\frac{\beta\alpha\theta \int_{\varepsilon^*}^{\varepsilon^H} [1-G(\varepsilon)]d\varepsilon}{\left\{1+\bar{\beta}\alpha\theta\left[\frac{\delta G(\varepsilon^*)}{1-\bar{\beta}\delta} + \frac{1-G(\varepsilon^*)}{\mu-\bar{\beta}}\right]\right\}(\mu-\bar{\beta})^2} & \text{if } \hat{\mu} < \mu < \bar{\mu}. \end{cases}$$

Clearly, $\partial \varepsilon^*/\partial \mu < 0$ for $\mu \in (\bar{\beta}, \hat{\mu})$ and for $\mu \in (\hat{\mu}, \bar{\mu})$. ■

A.4 Positive implications: asset prices

A.4.1 Monetary policy

Proof of Proposition 2. Recall that $\partial \varepsilon^*/\partial \mu < 0$ (Corollary 3). (i) From (8),

$$\frac{\partial \phi^s}{\partial \mu} = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta} \left[\mathbb{I}_{\{\bar{\beta} < \mu \leq \hat{\mu}\}} + \mathbb{I}_{\{\hat{\mu} < \mu < \bar{\mu}\}} \alpha \theta G(\varepsilon^*) \right] \frac{\partial \varepsilon^*}{\partial \mu} < 0.$$

(ii) Condition (9) implies $\partial \bar{\phi}^s/\partial \mu = \partial \varepsilon^*/\partial \mu + \partial \phi^s/\partial \mu < 0$. (iii) From (12) it is clear that $\partial Z/\partial \varepsilon^* > 0$, so $\partial Z/\partial \mu = (\partial Z/\partial \varepsilon^*)(\partial \varepsilon^*/\partial \mu) < 0$. From (10), $\partial \phi_t^m/\partial \mu = (y_t/A_t^m) \partial Z/\partial \mu < 0$. ■

For Proposition 3 we consider a formulation of the model where the length of the time period becomes arbitrarily short. This limiting economy can be interpreted as an approximation to a continuous-time version of our discrete-time economy.⁴⁹ To this end, generalize the baseline discrete-time model by allowing the period length to be an arbitrary constant, and then take

⁴⁹This formulation is useful since the model period in our quantitative implementation of the theory is very short (a trading day).

the limit as this constant becomes arbitrarily small. Let Δ denote the length of the model period, and define the discount rate, r , the expected dividend growth rate, g , the depreciation rate, d , and the money growth rate, m , as $\beta \equiv (1 + r\Delta)^{-1}$, $\bar{\gamma} \equiv 1 + g\Delta$, $\delta \equiv 1 - d\Delta$, $\mu \equiv 1 + m\Delta$. Over a time period of length Δ , the dividend is $y_t\Delta$, and consumption of the dividend good is $\varepsilon y_t\Delta$. In this context we focus on recursive equilibria where, as $\Delta \rightarrow 0$, real asset prices are time-invariant linear functions of the *dividend rate*, y_t . Specifically, let $\Phi_t^s(\Delta)$ and $\Phi_t^m(\Delta) A_t^m$ denote the real equity price and the real aggregate money balance, respectively, in the discrete-time economy with time periods of length Δ . We look for recursive equilibria of this discrete-time economy such that $\Phi_t^s(\Delta) = \Phi^s(\Delta) y_t\Delta$, $\bar{\Phi}_t^s(\Delta) = \bar{\Phi}^s(\Delta) y_t\Delta$, and $\Phi_t^m(\Delta) A_t^m = Z(\Delta) y_t\Delta$, where $\Phi^s(\Delta)$, $\bar{\Phi}^s(\Delta)$, and $Z(\Delta)$ are time-invariant functions with the property that $\lim_{\Delta \rightarrow 0} \Phi^s(\Delta) \Delta = \phi^s$, $\lim_{\Delta \rightarrow 0} \bar{\Phi}^s(\Delta) \Delta = \bar{\phi}^s$, and $\lim_{\Delta \rightarrow 0} Z(\Delta) \Delta = Z$, with $\phi^s, Z \in \mathbb{R}$.⁵⁰ The thresholds in (5) now generalize to $\hat{\mu} = 1 + \hat{m}\Delta$ and $\bar{\mu} = 1 + \bar{m}\Delta$, where

$$\hat{m} \equiv \frac{(1 - \alpha\theta)(\hat{\varepsilon} - \bar{\varepsilon})(r - g + d)}{\hat{\varepsilon}} - (r - g)$$

$$\bar{m} \equiv \frac{\alpha\theta(\bar{\varepsilon} - \varepsilon_L)(r - g + d)}{\bar{\varepsilon}} - (r - g).$$

Also, if we relabel $\underline{\mu} \equiv \bar{\beta}$, we now have $\underline{\mu} = 1 + \underline{m}\Delta$, where $\underline{m} \equiv g - r$. Then from part (ii) of Proposition 1, we know that a stationary monetary equilibrium exists if $m \in [\underline{m}, \bar{m})$. Notice that $\bar{m} < d$, so $m < d$ in any monetary equilibrium. The monetary equilibrium, i.e., (8), (9), (10), (12), and (13), generalize to

$$\begin{aligned} \Phi_t^s(\Delta) &= \Phi^s(\Delta) y_t\Delta \\ \Phi^s(\Delta) &= \begin{cases} \frac{(1+g\Delta)(1-d\Delta)}{1+r\Delta-(1+g\Delta)(1-d\Delta)} \bar{\varepsilon}^* & \text{if } \underline{m} < m \leq \hat{m} \\ \frac{(1+g\Delta)(1-d\Delta)}{1+r\Delta-(1+g\Delta)(1-d\Delta)} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] & \text{if } \hat{m} < m < \bar{m} \end{cases} \\ \bar{\Phi}_t^s(\Delta) &= \bar{\Phi}^s(\Delta) y_t\Delta, \text{ with } \bar{\Phi}^s(\Delta) = \varepsilon^* + \Phi^s(\Delta) \\ \Phi_t^m(\Delta) &= \frac{Z(\Delta) y_t\Delta}{A_t^m} \\ Z(\Delta) y_t\Delta &= \frac{\alpha G(\varepsilon^*) A_I^s + A_D^s}{\alpha [1 - G(\varepsilon^*)]} [\varepsilon^* y_t\Delta + \Phi_t^s(\Delta)] \end{aligned}$$

and

$$\frac{\int_{\varepsilon^*}^{\varepsilon^H} (\varepsilon - \varepsilon^*) dG(\varepsilon)}{\varepsilon^* + \frac{(1+g\Delta)(1-d\Delta)}{1+r\Delta} \left[\bar{\varepsilon} - \varepsilon^* + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] \mathbb{I}_{\{\hat{m} < m\}}} - \frac{[(1+m\Delta)(1+r\Delta)-(1+g\Delta)](1+r\Delta)}{[1+r\Delta-(1+g\Delta)(1-d\Delta)](1+g\Delta)} \frac{1}{\alpha\theta} = 0.$$

⁵⁰The discrete-time formulation we laid out previously, corresponds to a special case of this formulation with $\Delta = 1$, $\Phi_t^s(1) \equiv \phi_t^s$, $\Phi_t^m(1) \equiv \phi_t^m$, $\Phi^s(1) \equiv \phi^s$, and $Z(1) \equiv Z$.

As $\Delta \rightarrow 0$, these conditions become

$$\phi_t^s = \phi^s y_t, \text{ with } \phi^s = \begin{cases} \frac{1}{r-g+d} \varepsilon^* & \text{if } \underline{m} < m \leq \hat{m} \\ \frac{1}{r-g+d} \left[\bar{\varepsilon} + \alpha \theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] & \text{if } \hat{m} < m < \bar{m} \end{cases} \quad (59)$$

$$\bar{\phi}_t^s = \phi_t^s \quad (60)$$

$$\phi_t^m = \frac{Z}{A_t^m} y_t \quad (61)$$

$$Z = \frac{\alpha G(\varepsilon^*) A_I^s + A_D^s}{\alpha [1 - G(\varepsilon^*)]} \phi^s \quad (62)$$

$$0 = \frac{\alpha \theta \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*) dG(\varepsilon)}{\varepsilon^* + \left[\bar{\varepsilon} - \varepsilon^* + \alpha \theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon) dG(\varepsilon) \right] \mathbb{I}_{\{\hat{m} < m\}}} - \frac{r - g + m}{r - g + d}, \quad (63)$$

where $\phi_t^s \equiv \lim_{\Delta \rightarrow 0} \Phi_t^s(\Delta)$, $\bar{\phi}_t^s \equiv \lim_{\Delta \rightarrow 0} \bar{\Phi}_t^s(\Delta)$, and $\phi_t^m \equiv \lim_{\Delta \rightarrow 0} \Phi_t^m(\Delta)$.

Corollary 4 *In any monetary equilibrium of the continuous-time economy, $\partial \varepsilon^* / \partial r < 0$.*

Proof. From (63), it is clear that $\partial \varepsilon^* / \partial m < 0$, and

$$\frac{\partial \varepsilon^*}{\partial r} = \frac{d - m}{r - g + d} \frac{\partial \varepsilon^*}{\partial m}.$$

In any monetary equilibrium, $m < \bar{m} < d$, so $\partial \varepsilon^* / \partial r < 0$ in any monetary equilibrium. ■

Proof of Proposition 3. (i) From (59),

$$\frac{\partial \phi^s}{\partial r} = \frac{1}{r - g + d} \left\{ -\phi^s + \left[\mathbb{I}_{\{\underline{m} < m \leq \hat{m}\}} + \mathbb{I}_{\{\hat{m} < m < \bar{m}\}} \alpha \theta G(\varepsilon^*) \right] \frac{\partial \varepsilon^*}{\partial r} \right\} < 0,$$

where the inequality follows from Corollary 4. (ii) From (62) it is clear that $\partial Z / \partial \varepsilon^* > 0$, so $\partial Z / \partial r = (\partial Z / \partial \varepsilon^*) (\partial \varepsilon^* / \partial r) < 0$. From (61), $\partial \phi_t^m / \partial r = (y_t / A_t^m) \partial Z / \partial r < 0$. ■

A.4.2 OTC frictions: trading delays and market power

Proof of Proposition 4. From condition (13),

$$\frac{\partial \varepsilon^*}{\partial(\alpha \theta)} = \frac{\frac{\mu - \bar{\beta}}{\alpha \theta} [\varepsilon^* + \bar{\beta} \delta (\bar{\varepsilon} - \varepsilon^*) \mathbb{I}_{\{\hat{\mu} < \mu\}}]}{\bar{\beta} \alpha \theta (1 - \bar{\beta} \delta) [1 - G(\varepsilon^*)] + (\mu - \bar{\beta}) \{1 + \bar{\beta} \delta [\alpha \theta G(\varepsilon^*) - 1] \mathbb{I}_{\{\hat{\mu} < \mu\}}\}} > 0. \quad (64)$$

(i) From (8),

$$\frac{\partial \phi^s}{\partial(\alpha \theta)} = \begin{cases} \frac{\bar{\beta} \delta}{1 - \bar{\beta} \delta} \frac{\partial \varepsilon^*}{\partial(\alpha \theta)} > 0 & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{\bar{\beta} \delta}{1 - \bar{\beta} \delta} \left[\int_{\varepsilon_L}^{\varepsilon^*} G(\varepsilon) d\varepsilon + \alpha \theta G(\varepsilon^*) \frac{\partial \varepsilon^*}{\partial(\alpha \theta)} \right] > 0 & \text{if } \hat{\mu} < \mu < \bar{\mu}. \end{cases}$$

(ii) From (9), $\partial \bar{\phi}^s / \partial(\alpha \theta) = \partial \varepsilon^* / \partial(\alpha \theta) + \partial \phi^s / \partial(\alpha \theta) > 0$. (iii) For $\mu \in (\hat{\mu}, \bar{\mu})$, (12) implies $\partial Z / \partial \alpha = (\partial Z / \partial \varepsilon^*) (\partial \varepsilon^* / \partial \alpha) > 0$ and therefore $\partial \phi_t^m / \partial \alpha = (\partial Z / \partial \alpha) (y_t / A_t^m) > 0$. ■

A.5 Positive implications: financial liquidity

In this section, we use the theory to study the determinants of standard measures of market liquidity: liquidity provision by dealers, trade volume, and bid-ask spreads.

A.5.1 Liquidity provision by dealers

Broker-dealers in financial markets provide liquidity (*immediacy*) to investors by finding them counterparties for trade, or by trading with them out of their own account, effectively becoming their counterparty. The following result characterizes the effect of inflation on dealers' provision of liquidity by accumulating assets.

Proposition 7 *In the recursive monetary equilibrium: (i) dealers' provision of liquidity by accumulating assets, i.e., A_D^s , is nonincreasing in the inflation rate. (ii) For any μ close to $\bar{\beta}$, dealers' provision of liquidity by accumulating assets is nonmonotonic in $\alpha\theta$, i.e., $A_D^s = 0$ for $\alpha\theta$ close to 0 and close to 1, but $A_D^s > 0$ for intermediate values of $\alpha\theta$.*

Proof. (i) The result is immediate from the expression for A_D^s in Proposition 1. (ii) From (5) and (6),

$$\frac{\partial \hat{\mu}}{\partial (\alpha\theta)} = \bar{\beta} (1 - \bar{\beta}\delta) \left\{ \frac{(1 - \alpha\theta) \bar{\varepsilon}}{[1 - \alpha\theta G(\hat{\varepsilon})] \hat{\varepsilon}^2} \int_{\varepsilon_L}^{\hat{\varepsilon}} G(\varepsilon) d\varepsilon - \frac{\hat{\varepsilon} - \bar{\varepsilon}}{\hat{\varepsilon}} \right\}.$$

Notice that $\partial \hat{\mu} / \partial (\alpha\theta)$ approaches a positive value as $\alpha\theta \rightarrow 0$ and a negative value as $\alpha\theta \rightarrow 1$. Also, $\hat{\mu} \rightarrow \bar{\beta}$ both when $\alpha\theta \rightarrow 0$ and when $\alpha\theta \rightarrow 1$. Hence, $\mu > \bar{\beta} = \lim_{\alpha\theta \rightarrow 0} \hat{\mu} = \lim_{\alpha\theta \rightarrow 1} \hat{\mu}$ for a range of values of $\alpha\theta$ close to 0 and a range of values of $\alpha\theta$ close to 1. For those ranges of values of $\alpha\theta$, $A_D^s = 0$. In between those ranges there must exist values of $\alpha\theta$ such that $\mu < \hat{\mu}$, which implies $A_D^s > 0$. ■

Part (i) of Proposition 7 is related to the discussion that followed Proposition 1. The expected return from holding equity is larger for investors than for dealers with high inflation ($\mu > \hat{\mu}$) because in that case the expected resale value of equity in the OTC market is relatively low and dealers only buy equity to resell in the OTC market, while investors also buy it with the expectation of getting utility from the dividend flow. For low inflation ($\mu < \hat{\mu}$), dealers value equity more than investors because the OTC resale value is high and they have a higher probability of making capital gains from reselling than investors, and this trading advantage more than compensates for the fact that investors enjoy the additional utility from the dividend

flow. Part (ii) of Proposition 7 states that given a low enough rate of inflation, dealers' incentive to hold equity inventories overnight is nonmonotonic in the degree of OTC frictions as measured by $\alpha\theta$. In particular, dealers will not hold inventories if $\alpha\theta$ is either very small or very large. If $\alpha\theta$ is close to zero, few investors contact the interdealer market, and this makes the equity price in the OTC market very low, which in turn implies too small a capital gain to induce dealers to hold equity overnight. Conversely, if $\alpha\theta$ is close to one, a dealer has no trading advantage over an investor in the OTC market and since the investor gets utility from the dividend while the dealer does not, the willingness to pay for the asset in the centralized market is higher for the investor than for the dealer, and therefore it is investors and not dealers who carry the asset overnight into the OTC market.

A.5.2 Trade volume

Proof of Proposition 5. (i) Differentiate (15) to get

$$\frac{\partial \mathcal{V}}{\partial \mu} = 2\alpha G'(\varepsilon^*) (A^s - \delta \tilde{A}_D^s) \frac{\partial \varepsilon^*}{\partial \mu} < 0,$$

where the inequality follows from Corollary 3. (ii) Differentiate (15) to get

$$\frac{\partial \mathcal{V}}{\partial r} = 2\alpha G'(\varepsilon^*) (A^s - \delta \tilde{A}_D^s) \frac{\partial \varepsilon^*}{\partial r} < 0,$$

where the inequality follows from Corollary 4. (iii) From (15),

$$\begin{aligned} \frac{\partial \mathcal{V}}{\partial \theta} &= 2\alpha G'(\varepsilon^*) (A^s - \delta \tilde{A}_D^s) \frac{\partial \varepsilon^*}{\partial \theta} \\ \frac{\partial \mathcal{V}}{\partial \alpha} &= 2 \left[G(\varepsilon^*) + \alpha G'(\varepsilon^*) \frac{\partial \varepsilon^*}{\partial \alpha} \right] (A^s - \delta \tilde{A}_D^s), \end{aligned}$$

and both are positive since $\partial \varepsilon^* / \partial (\alpha\theta) > 0$ (see (64)). ■

A.5.3 Bid-ask spreads

Bid-ask spreads and intermediation fees are a popular measure of market liquidity as they constitute the main out-of-pocket transaction cost that investors bear in OTC markets. Lemma 1 shows that when dealers execute trades on behalf of their investors, they charge a fee $k_t(\mathbf{a}_t, \varepsilon)$ that is linear in the trade size. This means that when an investor with $\varepsilon > \varepsilon_t^*$ wants to buy equity, the dealer charges him an *ask price*, $p_t^a(\varepsilon) = p_t \phi_t^m + (1 - \theta)(\varepsilon - \varepsilon_t^*) y_t$ per share. When an investor with $\varepsilon < \varepsilon_t^*$ wants to sell, the dealer pays him a *bid price*, $p_t^b(\varepsilon) = p_t \phi_t^m -$

$(1 - \theta)(\varepsilon_t^* - \varepsilon)y_t$ per share. Define $\mathcal{S}_t^a(\varepsilon) = \frac{p_t^a(\varepsilon) - p_t \phi_t^m}{p_t \phi_t^m}$ and $\mathcal{S}_t^b(\varepsilon) = \frac{p_t \phi_t^m - p_t^b(\varepsilon)}{p_t \phi_t^m}$, i.e., the ask spread and bid spread, respectively, expressed as fractions of the price of the asset in the interdealer market. Then in a recursive equilibrium, the ask spread earned by a dealer when trading with an investor with $\varepsilon > \varepsilon^*$ is $\mathcal{S}^a(\varepsilon) = \frac{(1-\theta)(\varepsilon - \varepsilon^*)}{\varepsilon^* + \phi^s}$ and the bid spread earned by a dealer when trading with an investor with $\varepsilon < \varepsilon^*$ is $\mathcal{S}^b(\varepsilon) = \frac{(1-\theta)(\varepsilon^* - \varepsilon)}{\varepsilon^* + \phi^s}$. The average real spread earned by dealers is $\bar{\mathcal{S}} = \int [\mathcal{S}^a(\varepsilon) \mathbb{I}_{\{\varepsilon^* < \varepsilon\}} + \mathcal{S}^b(\varepsilon) \mathbb{I}_{\{\varepsilon < \varepsilon^*\}}] dG(\varepsilon)$. The change $\bar{\mathcal{S}}$ in response to changes in μ or α is ambiguous in general.⁵¹

A.6 Testable implications

Proof of Proposition 6. We start with the general model described in Section 6.1, which nests the model of Section 2 provided dealers do not hold asset inventories (the model of Section 6.1 considers an environment where dealers cannot hold inventories). The equilibrium conditions for the model of Section 6.1 for the case of no policy uncertainty (as is the case in the model of Section 2) are reported in Proposition 13 (Appendix C, Section C.3). Even without policy uncertainty, the model of Section 6.1 is more general than the model of Section 2 in that the former has multiple assets indexed by $s \in \{1, 2, \dots, N\}$ that differ in terms of the trading probability, α^s . Consider the equilibrium conditions (120) and (121), that determine ϕ^s and ε^{s*} for asset of type s . By following steps similar to those that preceded the proof of Proposition 3 in Section A.4, in the continuous-time limit of the discrete-time economy, conditions (120) and (121) become

$$\phi^s = \frac{1}{r - g + d} \left[\bar{\varepsilon} + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}} (\varepsilon^{s*} - \varepsilon) dG(\varepsilon) \right] \quad (65)$$

$$0 = \frac{\alpha^s \theta \int_{\varepsilon^{s*}}^{\varepsilon^H} (\varepsilon - \varepsilon^{s*}) dG(\varepsilon)}{\bar{\varepsilon} + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}} (\varepsilon^{s*} - \varepsilon) dG(\varepsilon)} - \frac{r - g + m}{r - g + d}. \quad (66)$$

Notice that (65) and (66), i.e., the equilibrium conditions that determine ϕ^s and ε^{s*} for each asset s in the multiple-asset model are identical to the corresponding conditions (59) and (63) for the continuous-time approximation to the single-asset model of Section 2 (again, provided dealers are assumed to hold no assets, e.g., as would be the case if they either cannot, or if they can, but $\hat{m} < m$).

⁵¹The reason is that the spread $\mathcal{S}^a(\varepsilon)$ charged to buyers is decreasing in ε^* while the spread $\mathcal{S}^b(\varepsilon)$ charged to sellers may be increasing in ε^* . For example, if $\mu \in (\hat{\beta}, \hat{\mu})$, it is easy to show $\partial \mathcal{S}^a(\varepsilon) / \partial \varepsilon^* = -\partial \mathcal{S}^b(\varepsilon) / \partial \varepsilon^* < 0$.

For any $x \in [\varepsilon_L, \varepsilon_H]$, define

$$I_B(x) \equiv \int_x^{\varepsilon_H} (\varepsilon - x) dG(\varepsilon)$$

$$I_S(x) \equiv \int_{\varepsilon_L}^x (x - \varepsilon) dG(\varepsilon)$$

and notice that $I'_B(x) = -[1 - G(x)]$ and $I'_S(x) = G(x)$, so a first-order Taylor approximation around $x_0 \in (\varepsilon_L, \varepsilon_H)$ gives

$$I_B(x) \approx I_B(x_0) - [1 - G(x_0)](x - x_0)$$

$$I_S(x) \approx I_S(x_0) + G(x_0)(x - x_0).$$

Let $\varepsilon^{s*} \equiv \varepsilon^{s*}(r, m, \alpha^s) \in (\varepsilon_L, \varepsilon_H)$ denote the value of ε^{s*} that solves (66) for given (r, m, α^s) , and let $\varepsilon_0^{s*} \equiv \varepsilon^{s*}(r_0, m_0, \alpha_0^s) \in (\varepsilon_L, \varepsilon_H)$ for some (r_0, m_0, α_0^s) . Use the Taylor approximation to get

$$(r - g + d)\phi^s \approx \bar{\varepsilon} + \alpha^s \theta [I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*})(\varepsilon^{s*} - \varepsilon_0^{s*})] \quad (67)$$

$$\frac{r - g + m}{r - g + d} \approx \frac{I_B(\varepsilon_0^{s*}) - [1 - G(\varepsilon_0^{s*})](\varepsilon^{s*} - \varepsilon_0^{s*})}{\frac{\bar{\varepsilon}}{\alpha^s \theta} + I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*})(\varepsilon^{s*} - \varepsilon_0^{s*})}. \quad (68)$$

Condition (68) implies

$$\varepsilon^{s*}(r, m, \alpha^s) \approx \frac{I_B(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]\varepsilon_0^{s*} - \left(\frac{r-g+m}{r-g+d}\right) \left[\frac{\bar{\varepsilon}}{\alpha^s \theta} + I_S(\varepsilon_0^{s*}) - G(\varepsilon_0^{s*})\varepsilon_0^{s*}\right]}{\left(\frac{r-g+m}{r-g+d}\right) G(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]}$$

and a first-order Taylor approximation gives

$$\varepsilon^{s*}(r, m, \alpha^s) \approx \varepsilon_0^{s*} + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r} (r - r_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m} (m - m_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s), \quad (69)$$

where

$$\frac{\partial \varepsilon^{s*}(r, m, \alpha^s)}{\partial r} = - \frac{\left[\frac{\bar{\varepsilon}}{\alpha^s \theta} + I_S(\varepsilon_0^{s*})\right] [1 - G(\varepsilon_0^{s*})] + I_B(\varepsilon_0^{s*}) G(\varepsilon_0^{s*})}{\left\{\left(\frac{r-g+m}{r-g+d}\right) G(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]\right\}^2} \frac{d - m}{(r - g + d)^2} \quad (70)$$

$$\frac{\partial \varepsilon^{s*}(r, m, \alpha^s)}{\partial m} = - \frac{G(\varepsilon_0^{s*}) I_B(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})] \left[\frac{\bar{\varepsilon}}{\alpha^s \theta} + I_S(\varepsilon_0^{s*})\right]}{(r - g + d) \left\{\left(\frac{r-g+m}{r-g+d}\right) G(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]\right\}^2} \quad (71)$$

$$\frac{\partial \varepsilon^{s*}(r, m, \alpha^s)}{\partial \alpha^s} = \frac{\left(\frac{r-g+m}{r-g+d}\right) \frac{\bar{\varepsilon}}{(\alpha^s)^2 \theta}}{\left(\frac{r-g+m}{r-g+d}\right) G(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]}. \quad (72)$$

Conditions (67) and (69) imply

$$\begin{aligned} \log \phi^s &\approx -\log(r - g + d) \\ &+ \log \left\{ \bar{\varepsilon} + \alpha^s \theta \left[I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*}) \left(\frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r} (r - r_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m} (m - m_0) \right. \right. \right. \\ &\left. \left. \left. + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s) \right) \right] \right\}. \end{aligned}$$

Without loss of generality, let $m = m_0$; then

$$\frac{\partial \log \phi^s}{\partial r} = -\frac{1}{r - g + d} + \frac{\alpha^s \theta G(\varepsilon_0^{s*}) \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r}}{\bar{\varepsilon} + \alpha^s \theta \left[I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*}) \left(\frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r} (r - r_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s) \right) \right]} \quad (73)$$

and

$$\frac{\partial^2 \log \phi^s}{\partial \alpha^s \partial r} = \frac{\theta G(\varepsilon_0^{s*}) \left[\bar{\varepsilon} - (\alpha^s)^2 \theta G(\varepsilon_0^{s*}) \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} \right] \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r}}{\left\{ \bar{\varepsilon} + \alpha^s \theta \left[I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*}) \left(\frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial r} (r - r_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s) \right) \right] \right\}^2}. \quad (74)$$

From (70), we see that in any monetary equilibrium, $\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s) / \partial r < 0$ (since $m < \bar{m} < d$, in any monetary equilibrium), so it is clear from (73) that $\partial \log \phi^s / \partial r < 0$. This establishes part (ii) in the statement of the proposition. By using (72), we know that

$$\bar{\varepsilon} - (\alpha^s)^2 \theta G(\varepsilon_0^{s*}) \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} = \frac{1 - G(\varepsilon_0^{s*})}{\left(\frac{r - g + m}{r - g + d} \right) G(\varepsilon_0^{s*}) + [1 - G(\varepsilon_0^{s*})]} \bar{\varepsilon} > 0. \quad (75)$$

With this inequality and $\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s) / \partial r < 0$, it is clear from (74) that $\partial^2 \log \phi^s / (\partial \alpha^s \partial r) < 0$. This establishes part (iv) in the statement of the proposition.

Without loss of generality, let $r = r_0$; then

$$\frac{\partial \log \phi^s}{\partial m} = \frac{\alpha^s \theta G(\varepsilon_0^{s*}) \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m}}{\bar{\varepsilon} + \alpha^s \theta \left[I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*}) \left(\frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m} (m - m_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s) \right) \right]} \quad (76)$$

and

$$\frac{\partial^2 \log \phi^s}{\partial \alpha^s \partial m} = \frac{\theta G(\varepsilon_0^{s*}) \left[\bar{\varepsilon} - (\alpha^s)^2 \theta G(\varepsilon_0^{s*}) \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} \right] \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m}}{\left\{ \bar{\varepsilon} + \alpha^s \theta \left[I_S(\varepsilon_0^{s*}) + G(\varepsilon_0^{s*}) \left(\frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial m} (m - m_0) + \frac{\partial \varepsilon^{s*}(r_0, m_0, \alpha_0^s)}{\partial \alpha^s} (\alpha^s - \alpha_0^s) \right) \right] \right\}^2}. \quad (77)$$

In Section 3, we defined $1 + \pi \equiv \mu / \bar{\gamma}$ for our baseline model. In the generalized discrete-time formulation with period of length Δ , this definition generalizes to $1 + \pi \Delta \equiv \frac{1 + m \Delta}{1 + g \Delta}$,

which for Δ small implies $\pi \approx m - g$. Hence it is clear that keeping g constant, $\partial \log \phi^s / \partial m$ and $\partial^2 \log \phi^s / (\partial \alpha^s \partial m)$ have the same sign as $\partial \log \phi^s / \partial \pi$ and $\partial^2 \log \phi^s / (\partial \alpha^s \partial \pi)$, respectively. From (71), we see that in any monetary equilibrium, $\partial \varepsilon^{s*} (r_0, m_0, \alpha_0^s) / \partial m < 0$, so it is clear from (76) that $\partial \log \phi^s / \partial m < 0$. This establishes part (i) in the statement of the proposition. With (75) and $\partial \varepsilon^{s*} (r_0, m_0, \alpha_0^s) / \partial m < 0$, it is clear from (77) that $\partial^2 \log \phi^s / (\partial \alpha^s \partial m) < 0$. This establishes part (iii) in the statement of the proposition. ■

A.7 Speculative premium

According to Proposition 1, in a monetary equilibrium the equity price, ϕ^s , is larger than the expected present discounted value that any agent assigns to the dividend stream, i.e., $\hat{\phi}_t^s \equiv [\bar{\beta}\delta / (1 - \bar{\beta}\delta)] \bar{\varepsilon} y_t$. We follow Harrison and Kreps (1978) and call the equilibrium value of the asset in excess of the expected present discounted value of the dividend, i.e., $\phi_t^s - \hat{\phi}_t^s$, the *speculative premium* that investors are willing to pay in anticipation of the capital gains they will reap when reselling the asset to investors with higher valuations in the future.⁵² Thus, we say investors exhibit *speculative behavior* if the prospect of reselling a stock makes them willing to pay more for it than they would if they were obliged to hold it forever. Investors exhibit speculative behavior in the sense that they buy with the expectation to resell, and naturally the asset price incorporates the value of this option to resell.

The speculative premium in a monetary equilibrium is $\mathcal{P}_t = \mathcal{P} y_t$, where

$$\mathcal{P} = \begin{cases} \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} (\varepsilon^* - \bar{\varepsilon}) & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \alpha \theta \int_{\varepsilon_L}^{\varepsilon^*} G(\varepsilon) d\varepsilon & \text{if } \hat{\mu} < \mu < \bar{\mu}. \end{cases}$$

The speculative premium is nonnegative in any monetary equilibrium, i.e., $\mathcal{P}_t \geq 0$, with “=” only if $\mu = \bar{\mu}$. Since $\partial \varepsilon^* / \partial \mu < 0$ (see Corollary 3), it is immediate that the speculative premium is decreasing in the rate of inflation. Intuitively, anticipated inflation reduces the

⁵²It is commonplace to define the *fundamental value* of the asset as the expected present discounted value of the dividend stream and to call any transaction value in excess of this benchmark a *bubble*. In fact, our notion of *speculative premium* corresponds to the notion of *speculative bubble* that is used in the modern literature on bubbles. See, e.g., Barlevy (2007), Brunnermeier (2008), Scheinkman and Xiong (2003a, 2003b), Scheinkman (2013), and Xiong (2013), who discuss Harrison and Kreps (1978) in the context of what is generally known as the *resale option theory of bubbles*. One could argue, of course, that the relevant notion of “fundamental value” should be calculated through market aggregation of diverse investor valuations and taking into account the monetary policy stance as well as all the details of the market structure in which the asset is traded (such as the frequency of trading opportunities and the degree of market power of financial intermediaries), which ultimately also factor into the asset price in equilibrium. We adopt the terminology used by Harrison and Kreps (1978) to avoid semantic controversies.

real money balances used to finance asset trading, which limits the ability of high-valuation traders to purchase the asset from low-valuation traders. As a result, the speculative premium is decreasing in μ . Since $\partial\varepsilon^*/\partial(\alpha\theta) > 0$ (see the proof of Proposition 4), the speculative premium is increasing in α and θ . Intuitively, the speculative premium is the value of the option to resell the equity to a higher valuation investor in the future, and the value of this resale option to the investor increases with the probability α that the investor gets a trading opportunity in an OTC trading round and with the probability θ that he can capture the gains from trade in those trades. So in low-inflation regimes, the model predicts large trade volume and a large speculative premium. The following proposition summarizes these results.

Proposition 8 *In the recursive monetary equilibrium: (i) $\partial\mathcal{P}/\partial\mu < 0$, (ii) $\partial\mathcal{P}/\partial(\alpha\theta) > 0$.*

Proof. (i) For $\bar{\beta} < \mu \leq \hat{\mu}$, $\partial\mathcal{P}/\partial\mu = [\bar{\beta}\delta/(1 - \bar{\beta}\delta)] (\partial\varepsilon^*/\partial\mu) < 0$, and for $\hat{\mu} < \mu < \bar{\mu}$, $\partial\mathcal{P}/\partial\mu = [\bar{\beta}\delta/(1 - \bar{\beta}\delta)] \alpha\theta G(\varepsilon^*) (\partial\varepsilon^*/\partial\mu) < 0$. (ii) For $\bar{\beta} < \mu \leq \hat{\mu}$, $\partial\mathcal{P}/\partial(\alpha\theta) = [\bar{\beta}\delta/(1 - \bar{\beta}\delta)] (\partial\varepsilon^*/\partial(\alpha\theta)) > 0$, and for $\hat{\mu} < \mu < \bar{\mu}$, $\partial\mathcal{P}/\partial\mu = [\bar{\beta}\delta/(1 - \bar{\beta}\delta)] \{ \alpha\theta G(\varepsilon^*) [\partial\varepsilon^*/\partial(\alpha\theta)] + \int_{\varepsilon_L}^{\varepsilon^*} G(\varepsilon) d\varepsilon \} > 0$. ■

Together, Proposition 5 and Proposition 8 imply that changes in the trading probability will generate a positive correlation between trade volume and the size of the speculative premium. The same is true of changes in the bargaining power.⁵³

Proposition 9 *Assume $G(\varepsilon; \sigma)$ is a differentiable function of the parameter σ that indexes a family of mean-preserving spreads, so that for any $\sigma < \sigma'$, $G(\cdot; \sigma')$ is a mean-preserving spread of $G(\cdot; \sigma)$. Then in the recursive monetary equilibrium, $\partial\phi^s/\partial\sigma > 0$ and $\partial\bar{\phi}^s/\partial\sigma > 0$.*

Proof of Proposition 9. From the definition of the mean-preserving spread, for any $\Delta > 0$,

$$\int_{\varepsilon_L}^x [G(\varepsilon; \sigma + \Delta) - G(\varepsilon; \sigma)] d\varepsilon \geq 0 \text{ for all } x \in (\varepsilon_L, \varepsilon_H),$$

with “=” if $x \in \{\varepsilon_L, \varepsilon_H\}$, and therefore

$$\lim_{\Delta \rightarrow 0} \int_{\varepsilon_L}^x \frac{[G(\varepsilon; \sigma + \Delta) - G(\varepsilon; \sigma)]}{\Delta} d\varepsilon = \int_{\varepsilon_L}^x G_\sigma(\varepsilon; \sigma) d\varepsilon \geq 0 \text{ for all } x \in (\varepsilon_L, \varepsilon_H),$$

⁵³The positive correlation between trade volume and the size of the speculative premium is a feature of historical episodes that are usually regarded as “bubbles”—a point emphasized by Scheinkman and Xiong (2003a, 2003b) and Scheinkman (2013).

with “=” if $x \in \{\varepsilon_L, \varepsilon_H\}$, where $G_\sigma(\varepsilon; \sigma) \equiv \partial G_\sigma(\varepsilon; \sigma) / \partial \sigma$. With this notation, the equilibrium mapping (13) is

$$T(x; \sigma) = \frac{\frac{1-\bar{\beta}\delta}{1-\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}} \int_x^{\varepsilon_H} [1 - G(\varepsilon; \sigma)] d\varepsilon}{x + \frac{\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}}{1-\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}} \left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^x G(\varepsilon; \sigma) d\varepsilon \right]} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta},$$

and the equilibrium ε^* satisfies $T(\varepsilon^*; \sigma) = 0$. By implicitly differentiating this condition, we get

$$\frac{\partial \varepsilon^*}{\partial \sigma} = - \frac{\frac{\alpha\theta\bar{\beta}}{1-\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}} \left(\delta\mathbb{I}_{\{\hat{\mu}<\mu\}} - \frac{1-\bar{\beta}\delta}{\mu-\bar{\beta}} \right) \int_{\varepsilon_L}^{\varepsilon^*} G_\sigma(\varepsilon; \sigma) d\varepsilon}{1 + \frac{\alpha\theta\bar{\beta}}{1-\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}} \left[G(\varepsilon^*; \sigma) \delta\mathbb{I}_{\{\hat{\mu}<\mu\}} + [1 - G(\varepsilon^*; \sigma)] \frac{1-\bar{\beta}\delta}{\mu-\bar{\beta}} \right]}.$$

If $\mu \in (\bar{\beta}, \hat{\mu})$, then $\partial \varepsilon^* / \partial \sigma > 0$ since $(1 - \bar{\beta}\delta) / (\mu - \bar{\beta}) - \delta\mathbb{I}_{\{\hat{\mu}<\mu\}} = (1 - \delta\bar{\beta}) / (\mu - \bar{\beta}) > 0$. If $\mu \in (\hat{\mu}, \bar{\mu})$, then $\partial \varepsilon^* / \partial \sigma > 0$ since

$$\delta\mu < \delta\bar{\mu} = 1 - (1 - \bar{\beta}\delta) \frac{\bar{\beta}\delta(1 - \alpha\theta)\bar{\varepsilon} + [1 - \bar{\beta}\delta(1 - \alpha\theta)]\varepsilon_L}{\bar{\beta}\delta\bar{\varepsilon} + (1 - \bar{\beta}\delta)\varepsilon_L} < 1$$

implies $-[\delta - (1 - \bar{\beta}\delta) / (\mu - \bar{\beta})] = (1 - \delta\mu) / (\mu - \bar{\beta}) > 0$. Given that $\partial \varepsilon^* / \partial \sigma > 0$ for all $\mu \in (\bar{\beta}, \bar{\mu})$, (8) and (9) imply $\partial \phi^s / \partial \sigma > 0$ and $\partial \bar{\phi}^s / \partial \sigma > 0$, respectively. ■

The following proposition shows there is a certain equivalence between α and G as fundamental determinants of trading activity.

Proposition 10 *Consider Economy A with contact probability α and distribution of valuations G on $[\varepsilon_L, \varepsilon_H]$ and Economy B with contact probability $\tilde{\alpha}$ and distribution of valuations \tilde{G} on $[\tilde{\varepsilon}_L, \tilde{\varepsilon}_H]$ (and all other primitives of Economy B are as in Economy A). Let ε^* and $\tilde{\varepsilon}^*$ denote the equilibrium marginal valuation for Economy A and Economy B, respectively. Then for any $\tilde{\alpha} > \alpha$, there exists a \tilde{G} such that*

$$\tilde{\varepsilon}^* = \frac{\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}(1 - \frac{\alpha}{\tilde{\alpha}})}{1 - \bar{\beta}\delta(1 - \mathbb{I}_{\{\hat{\mu}<\mu\}})} \bar{\varepsilon} + \left[1 - \frac{\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}(1 - \frac{\alpha}{\tilde{\alpha}})}{1 - \bar{\beta}\delta(1 - \mathbb{I}_{\{\hat{\mu}<\mu\}})} \right] \varepsilon^*,$$

and moreover, trade volume in Economy B is the same as in Economy A.

Proof of Proposition 10. In Economy A the marginal investor valuation, ε^* , is characterized by (13), while in Economy B the marginal investor valuation is the $\tilde{\varepsilon}^*$ that solves

$$\frac{(1 - \bar{\beta}\delta) \tilde{\alpha}\theta \int_{\tilde{\varepsilon}^*}^{\tilde{\varepsilon}_H} [1 - \tilde{G}(\varepsilon)] d\varepsilon}{(1 - \bar{\beta}\delta) \tilde{\varepsilon}^* + \bar{\beta}\delta \left[\int_{\tilde{\varepsilon}_L}^{\tilde{\varepsilon}_H} \varepsilon d\tilde{G}(\varepsilon) + \tilde{\alpha}\theta \int_{\tilde{\varepsilon}_L}^{\tilde{\varepsilon}^*} \tilde{G}(\varepsilon) d\varepsilon \right] \mathbb{I}_{\{\hat{\mu}<\mu\}}} - \frac{\mu - \bar{\beta}}{\bar{\beta}} = 0.$$

Define

$$\tilde{G}(\varepsilon) = \begin{cases} 0 & \text{for } \varepsilon \leq \tilde{\varepsilon}_L \\ \frac{\alpha}{\tilde{\alpha}} G(\varepsilon - c) + (1 - \frac{\alpha}{\tilde{\alpha}}) \mathbb{I}_{\{\varepsilon^* < \varepsilon - c\}} & \text{for } \tilde{\varepsilon}_L \leq \varepsilon \leq \tilde{\varepsilon}_H \\ 1 & \text{for } \tilde{\varepsilon}_H < \varepsilon \end{cases} \quad (78)$$

with $\tilde{\varepsilon}_L \equiv \varepsilon_L + c$, $\tilde{\varepsilon}_H \equiv \varepsilon_H + c$ and

$$c \equiv \frac{\bar{\beta}\delta \mathbb{I}_{\{\hat{\mu} < \mu\}}}{1 - \bar{\beta}\delta (1 - \mathbb{I}_{\{\hat{\mu} < \mu\}})} \left(1 - \frac{\alpha}{\tilde{\alpha}}\right) (\bar{\varepsilon} - \varepsilon^*). \quad (79)$$

With (78) and (79), the equilibrium mapping for Economy B becomes

$$\frac{(1 - \bar{\beta}\delta) \tilde{\alpha}\theta \int_{\tilde{\varepsilon}^* - c}^{\varepsilon_H} [1 - \frac{\alpha}{\tilde{\alpha}} G(z) - (1 - \frac{\alpha}{\tilde{\alpha}}) \mathbb{I}_{\{\varepsilon^* < z\}}] dz}{(1 - \bar{\beta}\delta) (\tilde{\varepsilon}^* - c) + \bar{\beta}\delta \left[\bar{\varepsilon} + \tilde{\alpha}\theta \int_{\varepsilon_L}^{\tilde{\varepsilon}^* - c} \left\{ \frac{\alpha}{\tilde{\alpha}} G(z) + (1 - \frac{\alpha}{\tilde{\alpha}}) \mathbb{I}_{\{\varepsilon^* < z\}} \right\} dz \right] \mathbb{I}_{\{\hat{\mu} < \mu\}}} - \frac{\mu - \bar{\beta}}{\bar{\beta}} = 0.$$

If we replace $\tilde{\varepsilon}^* = \varepsilon^* + c$ in this last expression, it reduces to (13), a condition that holds because ε^* is the equilibrium marginal valuation for Economy A . Hence, $\tilde{\varepsilon}^* = \varepsilon^* + c$ with c given by (79) is the equilibrium marginal valuation for Economy B . Notice that $\tilde{\alpha}\tilde{G}(\tilde{\varepsilon}^*) = \tilde{\alpha}\tilde{G}(\varepsilon^* + c) = \alpha G(\varepsilon^*)$, so (15) implies that trade volume in Economy B is the same as in Economy A . ■

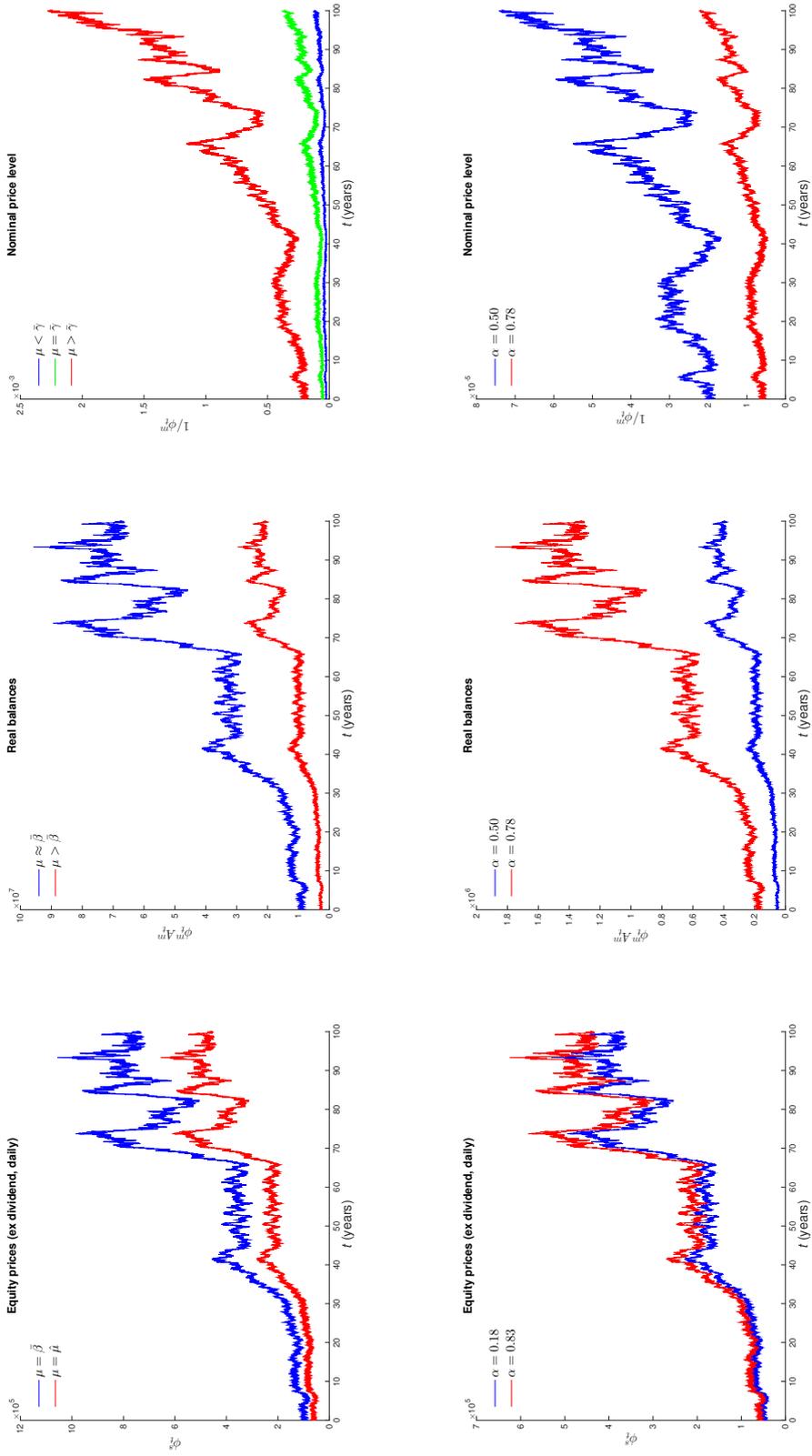


Figure 8: Effects of monetary policy and OTC frictions on asset prices.

B Supplementary material: Data, estimation, and simulation

B.1 Heteroskedasticity-based estimator

In this section we explain the H-based estimator used in Section 5.2. Rigobon and Sack (2004) show that the response of asset prices to changes in monetary policy can be identified based on the increase in the variance of policy shocks that occurs on days of FOMC announcements. They argue that this approach tends to be more reliable than the event-study approach based on daily data because identification relies on a weaker set of conditions.

The idea behind the heteroskedasticity-based estimator of Rigobon and Sack (2004) is as follows. Suppose the change in the policy rate, Δi_t , and Y_t (where Y_t could be the stock market return, \mathcal{R}_t^I , or the turnover rate, \mathcal{T}_t^I) are jointly determined by

$$\Delta i_t = \kappa Y_t + \varpi x_t + \epsilon_t \quad (80)$$

$$Y_t = \rho \Delta i_t + x_t + \eta_t, \quad (81)$$

where ϵ_t is a monetary policy shock and η_t is a shock to the asset price. To fix ideas, suppose $Y_t = \mathcal{R}_t^I$. Then equation (80) represents the monetary policy reaction to asset returns and possibly other variables represented by x_t . Equation (81) represents the reaction of asset prices to the policy rate and x_t . The disturbances ϵ_t and η_t are assumed to have no serial correlation and to be uncorrelated with each other and with x_t . We are interested in estimating the parameter ρ . Let Σ_v denote the variance of some variable v . If (80) and (81) were the true model and one were to run an OLS regression on an equation like (19), there would be a simultaneity bias if $\kappa \neq 0$ and $\Sigma_\eta > 0$, and an omitted variable bias if $\varpi \neq 0$ and $\Sigma_x > 0$. Conditions (80) and (81) can be solved for $\Delta i_t = \frac{1}{1-\rho\kappa} [\epsilon_t + \kappa\eta_t + (\kappa + \varpi)x_t]$ and $Y_t = \frac{1}{1-\rho\kappa} [\rho\epsilon_t + \eta_t + (1 + \rho\varpi)x_t]$. Divide the data sample into two subsamples: one consisting of FOMC policy announcement days and another consisting of the trading days immediately before the policy announcement days. In what follows we refer to these subsamples as S_1 and S_0 , respectively. Let Ω^k denote the covariance matrix of Δi_t and \mathcal{R}_t^I for $t \in S_k$, for $k \in \{0, 1\}$. Then

$$\Omega^k = \frac{1}{(1 - \rho\kappa)^2} \begin{bmatrix} \Omega_{11}^k & \Omega_{12}^k \\ \Omega_{21}^k & \Omega_{22}^k \end{bmatrix},$$

where $\Omega_{11}^k \equiv \Sigma_\epsilon^k + \kappa^2 \Sigma_\eta^k + (\kappa + \varpi)^2 \Sigma_x^k$, $\Omega_{12}^k = \Omega_{21}^k \equiv \rho \Sigma_\epsilon^k + \kappa \Sigma_\eta^k + (\kappa + \varpi)(1 + \rho\varpi) \Sigma_x^k$, $\Omega_{22}^k \equiv \rho^2 \Sigma_\epsilon^k + \Sigma_\eta^k + (1 + \rho\varpi)^2 \Sigma_x^k$, and Σ_x^k denotes the variance of variable x in subsample S_k , for

$k \in \{0, 1\}$. Provided $\Sigma_x^1 = \Sigma_x^0$ and $\Sigma_\eta^1 = \Sigma_\eta^0$,

$$\Omega^1 - \Omega^0 = \frac{\Sigma_\epsilon^1 - \Sigma_\epsilon^0}{(1 - \rho\kappa)^2} \begin{bmatrix} 1 & \rho \\ \rho & \rho^2 \end{bmatrix}.$$

Hence, if $\Sigma_\epsilon^1 - \Sigma_\epsilon^0 > 0$, then ρ can be identified from the difference in the covariance matrices of the two subsamples. This suggests a natural way to estimate ρ . Replace Ω^1 and Ω^0 with their sample estimates, denoted $\hat{\Omega}^1$ and $\hat{\Omega}^0$. Define $\hat{\Omega} \equiv \hat{\Omega}^1 - \hat{\Omega}^0$ and use $\hat{\Omega}_{ij}$ to denote the (i, j) element of $\hat{\Omega}$. Then ρ can be estimated by $\hat{\Omega}_{12}/\hat{\Omega}_{11} \equiv \hat{\rho}$. Rigobon and Sack (2004) show that this estimate can be obtained by regressing \mathcal{R}_t^I on Δi_t over the combined sample $S_0 \cup S_1$ using a standard instrumental variables regression.

The standard deviation of Δi_t is 4.37 basis points (bps) in subsample S_0 and 6.29 bps in subsample S_1 . The standard deviation of \mathcal{R}_t^I is 86.10 bps in subsample S_0 and 92.96 bps in subsample S_1 . The correlation between Δi_t and \mathcal{R}_t^I is 0.057 in subsample S_0 and -0.37 in subsample S_1 . Stock returns are more volatile on the days of monetary policy announcements than on other days, which is consistent with policy actions inducing some reaction in the stock market. The relatively large negative correlation between the policy rate and stock returns for announcement days contrasts with the much smaller and positive correlation for non-announcement days, suggesting that the negative effect of surprise increases in the nominal rate on stock prices that has been documented in the empirical literature (e.g., Bernanke and Kuttner, 2005, Rigobon and Sack, 2004).

B.2 High-frequency IV estimator

In this section we consider a version of the event-study estimator that, instead of *daily* changes in the interest rate, uses intraday high-frequency tick-by-tick interest rate data to isolate the change in the interest rate that takes place over a narrow window around each policy announcement. We refer to this as the *high-frequency instrumental variable estimator* (or “HFIV” estimator, for short).

Specifically, the HFIV estimator is obtained by estimating (19), where instead of directly using the daily change in the 3-month Eurodollar future rate, we instrument for it using the daily *imputed change* in the 30-day federal funds futures rate from the level it has 20 minutes after the FOMC announcement and the level it has 10 minutes before the FOMC announcement.⁵⁴ By

⁵⁴ By “daily imputed” we mean that in order to interpret the change in the federal funds futures rate as the surprise component of the change in the daily policy rate, it is adjusted for the fact that the federal funds futures

focusing on changes in a proxy for the policy rate in a very narrow 30-minute window around the time of the policy announcement, the resulting HFIV estimator addresses the omitted variable bias and the concern that the Eurodollar futures rate may itself respond to market conditions on policy announcement days.

The data for the high-frequency interest change are constructed as follows. For each announcement day $t \in S_1$, we define $z_t \equiv i_{t,m_t^*+20} - i_{t,m_t^*-10}$, where $i_{t,m}$ denotes the (daily imputed) 30-day federal funds futures rate on minute m of day t , and for any $t \in S_1$, m_t^* denotes the time of day (measured in minutes) when the FOMC announcement was made.⁵⁵ We then estimate b in (19) using the following two-stage least squares (2SLS) procedure. Define $\Delta i_t^{ed} \equiv i_t^{ed} - i_{t-1}^{ed}$, where i_t^{ed} denotes the rate implied (for day t) by the 3-month Eurodollar futures contract with closest expiration date at or after day t . First, run the regression $\Delta i_t^{ed} = \kappa_0 + \kappa z_t + \eta_t$ on sample S_1 (where η_t is an error term) to obtain the OLS estimates of κ_0 and κ , namely $\hat{\kappa}_0$ and $\hat{\kappa}$. Second, construct the fitted values $\hat{z}_t \equiv \hat{\kappa}_0 + \hat{\kappa} z_t$ and run the event-study regression (19) setting $\Delta i_t = \hat{z}_t$.

B.3 More on disaggregative announcement-day effects

In Section 5.3 and Section B.2, we sorted stocks into 20 portfolios according to the level of turnover of each individual stock and found that changes in the nominal rate affect stocks with different turnover liquidity differently, with more liquid stocks responding more than less liquid stocks. In this section, we complement that analysis by using an alternative procedure to sort stocks into portfolios. Specifically, in this section we sort stocks according to the sensitivity of their individual return to changes in an aggregate (marketwide) measure of turnover. This alternative criterion is useful for two reasons. First, it will allow us to control for some differences across stocks, such as the conventional risk factors used in empirical asset-pricing models. Second, this sorting criterion emphasizes the responsiveness of the individual stock return to changes in an aggregate measure of turnover, which is another manifestation of the transmission mechanism that operates in the theory. To construct the portfolios, we proceed as follows.

contracts settle on the effective federal funds rate *averaged over the month covered by the contract*. See Section B.4.3 for details.

⁵⁵We use the data set constructed by Gorodnichenko and Weber (2016) with tick-by-tick data of the federal funds futures trading on the CME Globex electronic trading platform (as opposed to the open-outcry market). The variable we denote as z_t is the same variable that Gorodnichenko and Weber denote as v_t . The data are available at http://faculty.chicagobooth.edu/michael.weber/research/data/replication_dataset_gw.xlsx.

For each individual stock s in our sample, we use daily time-series data to run

$$\mathcal{R}_t^s = \alpha^s + \beta_0^s \mathcal{T}_t^I + \sum_{j=1}^K \beta_j^s f_{j,t} + \varepsilon_t^s, \quad (82)$$

where ε_t^s is an error term, \mathcal{R}_t^s is the daily stock return (between day t and day $t - 1$), \mathcal{T}_t^I is the aggregate (marketwide) turnover rate on day t , and $\{f_{j,t}\}_{j=1}^K$ are K pricing factors. We set $K = 3$, with $f_{1,t} = MKT_t$, $f_{2,t} = HML_t$, and $f_{3,t} = SMB_t$, where MKT_t is a broad measure of the market excess return, HML_t is the return of a portfolio of stocks with high book-to-market value minus the return of a portfolio of stocks with low book-to-market value, and SMB_t is the return of a portfolio of small-cap stocks minus the return of a portfolio of large-cap stocks. That is, MKT_t is the typical CAPM factor, while HML_t and SMB_t are the long-short spreads constructed by sorting stocks according to book-to-market value and market capitalization, respectively, as in the Fama and French (1993) three-factor model.⁵⁶ Let t_k denote the day of the k^{th} policy announcement (we use 133 policy announcement days from our sample period 1994-2007). For each stock s , regression (82) is run 133 times, once for each policy announcement day, each time using the sample of all trading days between day t_{k-1} and day t_k . Thus, for each stock s we obtain 532 estimates, $\{\{\beta_j^s(k)\}_{j=0}^3\}_{k=1}^{133}$, where $\beta_j^s(k)$ denotes the estimate for the beta corresponding to factor j for stock s , estimated on the sample consisting of all trading days between the policy announcement days t_{k-1} and t_k . For each policy announcement day, t_k , we sort all NYSE stocks into 20 portfolios by assigning stocks with $\beta_0^s(k)$ ranked between the $[5(i-1)]^{\text{th}}$ percentile and $(5i)^{\text{th}}$ percentile to the i^{th} portfolio, for $i = 1, \dots, 20$. For each portfolio $i \in \{1, \dots, 20\}$ constructed in this manner, we compute the daily return, \mathcal{R}_t^i , and the daily change in the turnover rate, $\mathcal{T}_t^i - \mathcal{T}_{t-1}^i$, and run the event-study regression (19) portfolio-by-portfolio, first with $Y_t^i = \mathcal{R}_t^i$ and then with $Y_t^i = \mathcal{T}_t^i - \mathcal{T}_{t-1}^i$, as in

⁵⁶In order to construct the Fama-French factors HML_t and SMB_t , stocks are sorted into six portfolios obtained from the intersections of two portfolios formed on size (as measured by market capitalization and labeled “Small” and “Big”) and three portfolios formed on the ratio of book value to market value (labeled “Value,” “Neutral,” and “Growth”). Then $SMB_t = (1/3)(\mathcal{R}_t^{SG} + \mathcal{R}_t^{SN} + \mathcal{R}_t^{SV}) - (1/3)(\mathcal{R}_t^{BG} + \mathcal{R}_t^{BN} + \mathcal{R}_t^{BV})$ and $HML_t = (1/2)(\mathcal{R}_t^{SV} + \mathcal{R}_t^{BV}) - (1/2)(\mathcal{R}_t^{SG} + \mathcal{R}_t^{BG})$, where \mathcal{R}_t^{BG} denotes the return on portfolio “Big-Growth,” \mathcal{R}_t^{SV} denotes the return on portfolio “Small-Value,” and so on. For a detailed description of the breakpoints used to define the six portfolios, see Kenneth French’s website, http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/Data_Library/six_portfolios. The CAPM factor, MKT_t , is a broad measure of the market excess return, specifically, the value-weighted return of all CRSP firms incorporated in the United States and listed on the NYSE, AMEX, or NASDAQ that have a CRSP share code of 10 or 11 at the beginning of month t , good shares and price data at the beginning of t , and good return data for t minus the one-month Treasury bill rate (from Ibbotson Associates). The data for the three Fama-French factors were obtained from Wharton Research Data Services (WRDS).

Section 5.3.

For each of the 20 portfolios, Table 4 reports estimates of the responses (on the day of the policy announcement) of the return of the portfolio to a 1 pp increase in the policy rate. Estimates are negative, as predicted by the theory. Also as predicted by the theory, the magnitude of the estimates tends to be larger for portfolios with higher indices. From these estimates we learn that stocks whose returns are more sensitive to aggregate measures of aggregate market turnover tend to experience larger declines in returns in response to unexpected increases in the nominal rate. This finding is in line with the turnover-liquidity channel of monetary policy.

Notice that by sorting portfolios on the β_0 's estimated from (82), we are controlling for the three standard Fama-French factors. To explore how the portfolios sorted in this manner vary in terms of the three standard Fama-French factors, we construct the series of monthly return for each of the 20 portfolios for the period 1994-2007, $\{(\mathcal{R}_t^i)_{i=1}^{20}\}$, and run (82) to estimate the vector of betas, $\{\{\beta_j^i\}_{i=1}^{20}\}_{j=0}^3$. The estimated betas corresponding to each portfolio are displayed in Figure 9.⁵⁷ Notice that there is no correlation between the turnover-liquidity betas, $\{\beta_0^i\}_{i=1}^{20}$, and the CAPM betas, $\{\beta_1^i\}_{i=1}^{20}$. To get a sense of whether the different cross-portfolio responses of returns to policy shocks documented in Table 4 can be accounted for by the standard CAPM, consider the following back-of-the-envelope calculation. Let b denote the effect of a 1 bp increase in the policy rate on the marketwide stock return on the day of the policy announcement (e.g., the E-based estimate obtained from running (19) with $Y_t^I = \mathcal{R}_t^I$). Then according to the basic CAPM model, the effect on portfolio $i \in \{1, \dots, 20\}$ would be $\tilde{b}^i \equiv \beta_1^i \times b$, where $\{\beta_1^i\}_{i=1}^{20}$ is the vector of betas estimated on monthly data for each of the 20 portfolios sorted on β_0^i (plotted in Figure 9). Figure 10 plots $\{(i, \tilde{b}^i)\}_{i=1}^{20}$ and $\{(i, b^i)\}_{i=1}^{20}$, where $\{b^i\}_{i=1}^{20}$ corresponds to the E-based estimates for the effect of monetary policy on returns reported in Table 4.

B.4 VAR estimation

B.4.1 Identification

We conjecture that the data, $\{Y_t\}$ with $Y_t \in \mathbb{R}^n$, correspond to an equilibrium that can be approximated by a structural vector autoregression (SVAR),

$$KY_t = \sum_{j=1}^J C_j Y_{t-j} + \varepsilon_t, \quad (83)$$

⁵⁷The vector $\{\beta_0^i\}_{i=1}^{20}$ shown in the figure has been normalized by dividing it by $|\beta_0^1|$.

where K and C_j are $n \times n$ matrices, $J \geq 1$ is an integer that denotes the maximum number of lags, and $\varepsilon_t \in \mathbb{R}^n$ is a vector of structural shocks, with $\mathbb{E}(\varepsilon_t) = 0$, $\mathbb{E}(\varepsilon_t \varepsilon_t') = I$, and $\mathbb{E}(\varepsilon_t \varepsilon_s') = 0$ for $s \neq t$, where 0 is a conformable matrix of zeroes and I denotes the n -dimensional identity. If K is invertible, (83) can be represented by the reduced-form VAR

$$Y_t = \sum_{j=1}^J B_j Y_{t-j} + u_t, \quad (84)$$

where $B_j = K^{-1}C_j$ and

$$u_t = K^{-1}\varepsilon_t \quad (85)$$

is an error term with

$$\Xi \equiv \mathbb{E}(u_t u_t') = K^{-1}K^{-1'}. \quad (86)$$

The reduced-form VAR (84) can be estimated to obtain the matrices $\{B_j\}_{j=1}^J$, and the residuals $\{u_t\}$ from the estimation can be used to calculate Ξ . From (85), we know that the disturbances of the reduced-form VAR (84) are linear combinations of the structural shocks, ε_t , so in order to use (84) and the estimates $\{B_j\}_{j=1}^J$ to compute the impulse responses to the structural shocks, it is necessary to find the n^2 elements of the matrix K^{-1} . However, given the known covariance matrix Ξ , (86) only provides $n(n+1)/2$ independent equations involving the elements of K^{-1} , so $n(n-1)/2$ additional independent conditions would be necessary to find all elements of K^{-1} . This is the well-known identification problem of the SVAR (83). Only three specific elements of K^{-1} are relevant for our analysis. To find them, we use an identification scheme that relies on external instruments.⁵⁸

The VAR we estimate consists of three variables, i.e., $Y_t = (i_t, \mathcal{R}_t^I, \mathcal{T}_t^I)'$, where i_t , \mathcal{R}_t^I , and \mathcal{T}_t^I are the measures of the policy rate, the stock return, and turnover described in Sections 5.1 and 5.2. Denote $\varepsilon_t = (\varepsilon_t^i, \varepsilon_t^{\mathcal{R}}, \varepsilon_t^{\mathcal{T}})'$, $u_t = (u_t^i, u_t^{\mathcal{R}}, u_t^{\mathcal{T}})'$, and

$$K^{-1} = \begin{bmatrix} k_i^i & k_i^{\mathcal{R}} & k_i^{\mathcal{T}} \\ k_{\mathcal{R}}^i & k_{\mathcal{R}}^{\mathcal{R}} & k_{\mathcal{R}}^{\mathcal{T}} \\ k_{\mathcal{T}}^i & k_{\mathcal{T}}^{\mathcal{R}} & k_{\mathcal{T}}^{\mathcal{T}} \end{bmatrix}.$$

Then $u_t = K^{-1}\varepsilon_t$ can be written as

$$\begin{bmatrix} u_t^i \\ u_t^{\mathcal{R}} \\ u_t^{\mathcal{T}} \end{bmatrix} = \begin{bmatrix} k_i^i \\ k_{\mathcal{R}}^i \\ k_{\mathcal{T}}^i \end{bmatrix} \varepsilon_t^i + \begin{bmatrix} k_i^{\mathcal{R}} \\ k_{\mathcal{R}}^{\mathcal{R}} \\ k_{\mathcal{T}}^{\mathcal{R}} \end{bmatrix} \varepsilon_t^{\mathcal{R}} + \begin{bmatrix} k_i^{\mathcal{T}} \\ k_{\mathcal{R}}^{\mathcal{T}} \\ k_{\mathcal{T}}^{\mathcal{T}} \end{bmatrix} \varepsilon_t^{\mathcal{T}}. \quad (87)$$

⁵⁸The identification methodology has been used by Mertens and Ravn (2013), Stock and Watson (2012), Gertler and Karadi (2015), Hamilton (2003), and Kilian (2008a, 2008b), among others.

Since we are only interested in the impulse responses for the monetary shock, ε_t^i , it suffices to find the first column of K^{-1} . The identification problem we face, of course, stems from the fact that the structural shocks, $(\varepsilon_t^i, \varepsilon_t^{\mathcal{R}}, \varepsilon_t^{\mathcal{T}})$, are unobservable and some of the elements of K^{-1} are unknown (three elements are unknown in this 3×3 case). Suppose we had data on $\{\varepsilon_t^i\}$. Then we could run the regression $u_t^i = \kappa_i^i \varepsilon_t^i + \eta_t$ to estimate κ_i^i , where η_t is an error term. From (87) we have $\eta_t = k_i^{\mathcal{R}} \varepsilon_t^{\mathcal{R}} + k_i^{\mathcal{T}} \varepsilon_t^{\mathcal{T}}$, so $\mathbb{E}(\varepsilon_t^i \eta_t) = \mathbb{E}[\varepsilon_t^i (k_i^{\mathcal{R}} \varepsilon_t^{\mathcal{R}} + k_i^{\mathcal{T}} \varepsilon_t^{\mathcal{T}})] = 0$ (since we are assuming $\mathbb{E}(\varepsilon_t \varepsilon_t') = I$), and thus the estimate of κ_i^i could be used to identify k_i^i (up to a constant) via the population regression of u_t^i onto ε_t^i . Since ε_t^i is unobservable, one natural alternative is to find a proxy (instrumental) variable for it. Suppose there is a variable z_t such that

$$\mathbb{E}(z_t \varepsilon_t^{\mathcal{R}}) = \mathbb{E}(z_t \varepsilon_t^{\mathcal{T}}) = 0 < \mathbb{E}(z_t \varepsilon_t^i) \equiv v \text{ for all } t.$$

Then

$$\Lambda \equiv \mathbb{E}(z_t u_t) = K^{-1} \mathbb{E}(z_t \varepsilon_t) = (k_i^i, k_i^{\mathcal{R}}, k_i^{\mathcal{T}})' v. \quad (88)$$

Since $\Lambda = (\Lambda_1, \Lambda_2, \Lambda_3)'$ is a known (3×1) vector, we can identify the coefficients of interest, $(k_i^i, k_i^{\mathcal{R}}, k_i^{\mathcal{T}})$ up to the sign of the scalar v . To see this, notice (88) implies

$$v k_i^i = \Lambda_1 \quad (89)$$

$$v k_i^{\mathcal{R}} = \Lambda_2 \quad (90)$$

$$v k_i^{\mathcal{T}} = \Lambda_3 \quad (91)$$

with

$$v^2 = \mathbb{E}(z_t u_t)' \Xi^{-1} \mathbb{E}(z_t u_t). \quad (92)$$

Since the sign of v is unknown, we could look for restrictions that do not involve v , and in this case these conditions only provide two additional restrictions on $(k_i^i, k_i^{\mathcal{R}}, k_i^{\mathcal{T}})$, i.e., combining (89) with (90), and (89) with (91), yields

$$\frac{k_i^{\mathcal{R}}}{k_i^i} = \frac{\Lambda_2}{\Lambda_1} \quad (93)$$

$$\frac{k_i^{\mathcal{T}}}{k_i^i} = \frac{\Lambda_3}{\Lambda_1}. \quad (94)$$

Thus, $k_i^{\mathcal{R}}$ and $k_i^{\mathcal{T}}$ are identified. From (89), k_i^i is also identified but up to the sign of v .

Notice that if we run a 2SLS regression of $u_t^{\mathcal{R}}$ on u_t^i using z_t as an instrument for u_t^i , then the estimate of the slope coefficient on this regression is Λ_2/Λ_1 . Similarly, Λ_3/Λ_1 corresponds

to the instrumental variable estimate of the slope coefficient of a regression of $u_t^{\mathcal{T}}$ on u_t^i using z_t as an instrument for u_t^i .

In our application, as an instrument for the structural monetary policy shock, ε_t^i , we use the (daily imputed) change in the 30-day federal funds futures from the level it has 10 minutes before the FOMC announcement and the level it has 20 minutes after the FOMC announcement.⁵⁹ That is, we restrict our sample to $t \in S_1$ and set $\{z_t\} = \{i_{t,m_t^*+20} - i_{t,m_t^*-10}\}$, where $i_{t,m}$ denotes the (daily imputed) 30-day federal funds futures rate on minute m of day t , and for any $t \in S_1$, m_t^* denotes the time of day (measured in minutes) when the FOMC announcement was made.⁶⁰ All this leads to the following procedure, used by Mertens and Ravn (2013), Stock and Watson (2012), and Gertler and Karadi (2015), to identify the coefficients needed to estimate the empirical impulse responses to a monetary policy shock:

Step 1: Estimate the reduced-form VAR by least squares over the whole sample of all trading days to obtain the coefficients $\{B_j\}_{j=1}^J$ and the residuals $\{u_t\}$.

Step 2: Run the regression $u_t^i = \kappa_0 + \kappa^i z_t + \eta_t$ on sample S_1 to obtain the OLS estimates of κ_0 and κ^i , namely $\hat{\kappa}_0$ and $\hat{\kappa}^i$, and construct the fitted values $\hat{u}_t^i = \hat{\kappa}_0 + \hat{\kappa}^i z_t$.

Step 3: Run the regressions $u_t^{\mathcal{R}} = \kappa_0 + \kappa^{\mathcal{R}} \hat{u}_t^i + \eta_t$ and $u_t^{\mathcal{T}} = \kappa_0 + \kappa^{\mathcal{T}} \hat{u}_t^i + \eta_t$ on sample S_1 to obtain the OLS estimates of $\kappa^{\mathcal{R}}$ and $\kappa^{\mathcal{T}}$, namely $\hat{\kappa}^{\mathcal{R}}$ and $\hat{\kappa}^{\mathcal{T}}$. Since $\hat{\kappa}^{\mathcal{R}} = \Lambda_2/\Lambda_1$ and $\hat{\kappa}^{\mathcal{T}} = \Lambda_3/\Lambda_1$, (93) and (94) imply $\hat{\kappa}^{\mathcal{R}} = k_{\mathcal{R}}^i/k_i^i$ and $\hat{\kappa}^{\mathcal{T}} = k_{\mathcal{T}}^i/k_i^i$.

For the purpose of getting impulse responses with respect to the shock ε_t^i , the scale and sign of k_i^i are irrelevant since the shock ε_t^i is typically normalized to have any desired impact on a given variable.⁶¹ For example, in our impulse responses we normalize the shock ε_t^i so that it

⁵⁹By “daily imputed” we mean that in order to interpret the change in the federal funds futures rate as the surprise component of the change in the daily policy rate, it is adjusted for the fact that the federal funds futures contracts settle on the effective federal funds rate *averaged over the month covered by the contract*. See Section B.4.3 for details.

⁶⁰We use the data set constructed by Gorodnichenko and Weber (2016) with tick-by-tick data of the federal funds futures trading on the CME Globex electronic trading platform (as opposed to the open-outcry market). The variable we call z_t is the same variable that Gorodnichenko and Weber denote as v_t . Their data are available at http://faculty.chicagobooth.edu/michael.weber/research/data/replication_dataset_gw.xlsx. We have also performed the estimations using a different instrument for the high-frequency external identification scheme, namely the 3-month Eurodollar rate (on the nearest futures contract to expire after the FOMC announcement) from the level it has 10 minutes before the FOMC announcement and the level it has 20 minutes after the FOMC announcement. That is, we restrict our sample to $t \in S_1$ and set $\{z_t\} = \{i_{t,m_t^*+20}^{ed} - i_{t,m_t^*-10}^{ed}\}$, where $i_{t,m}^{ed}$ denotes the 3-month Eurodollar futures rate on minute m of day t , and for any $t \in S_1$, m_t^* denotes the time of day (measured in minutes) when the FOMC announcement was made. The results were essentially the same.

⁶¹Alternatively, (89) and (92) can be combined to get $k_i^i = \Lambda_1/v$, which is then identified up to the sign of v .

induces a 1 pp increase in the level of the policy rate i_t on impact. To see this, consider (87) with $\varepsilon_t^{\mathcal{R}} = \varepsilon_t^{\mathcal{T}} = 0$. Then for any k_t^i , the shock that induces an x pp increase in the level of the policy rate on impact (e.g., at $t = 0$) is $\varepsilon_0^i = (x/100)/k_t^i = (x/100)/(\Lambda_1/v)$.

B.4.2 Confidence intervals for impulse responses

The 95 percent confidence intervals for the impulse response coefficients estimated from the data are computed using a recursive wild bootstrap using 10,000 replications, as in Gonçalves and Kilian (2004) and Mertens and Ravn (2013). The procedure is as follows. Given the estimates of the reduced-form VAR, $\{\hat{B}_j\}_{j=1}^J$, and the residual, $\{\hat{u}_t\}$, we generate bootstrap draws, $\{Y_t^b\}$, recursively, by $Y_t^b = \sum_{j=1}^J \hat{B}_j Y_{t-j} + e_t^b \hat{u}_t$, where e_t^b is the realization of a scalar random variable taking values of -1 or 1 , each with probability $1/2$. Our identification procedure also requires us to generate bootstrap draws for the proxy variable, $\{z_t^b\}$, so following Mertens and Ravn (2013), we generate random draws for the proxy variable via $z_t^b = e_t^b z_t$. We then use the bootstrap samples $\{Y_t^b\}$ and $\{z_t^b\}$ to reestimate the VAR coefficients and compute the associated impulse responses (applying the covariance restrictions implied by the bootstrapped instrument z_t^b). This gives one bootstrap estimate of the impulse response coefficients. The confidence intervals are the percentile intervals of the distribution of 10,000 bootstrap estimates for the impulse response coefficients.

B.4.3 Changes in federal funds future rate and unexpected policy rate changes

Fix a month, s , and let the intervals $\{[t, t+1]\}_{t=1}^T$ denote the T days of the month. Let $\{f_{s,t}^0\}_{t=1}^T$ denote the market prices of the federal funds futures contract *at the end* of day t of month s . The superscript “0” indicates that the contract corresponds to the current month, s .⁶² Let $\{r_t\}_{t=1}^T$ be the (average) daily federal funds rate calculated *at the end* of day t . Finally, for $j = 1, \dots, T - t$, let $E_t r_{t+j}$ denote the expectation of the spot federal funds rate on day $t + j$ conditional on the information available at the end of day t . Then, since federal funds futures contracts settle on the average daily rate of the month, we have

$$f_{s,t}^0 = \frac{1}{T} \left[\sum_{i=1}^t r_i + \sum_{i=t+1}^T E_t r_i \right], \text{ for } t = 1, \dots, T.$$

⁶²Contracts can range from 1 to 5 months. For example, $f_{s,t}^5$ would be the price of the 5-month forward on day t of month s .

Hence, for $t = 1, \dots, T$,

$$f_{s,t}^0 - f_{s,t-1}^0 = \frac{1}{T}r_t - \frac{1}{T}E_{t-1}r_t + \frac{1}{T}\sum_{i=t+1}^T E_t r_i - \frac{1}{T}\sum_{i=t+1}^T E_{t-1}r_i,$$

where $f_{s,0}^0 \equiv f_{s-1,T}^1$. Assume the federal funds rate changes at most once during the month, and suppose it is known that the announcement takes place at the beginning of day $t \geq 1$.⁶³ Then

$$\begin{aligned} E_t r_i &= r_t \text{ for } i = t, \dots, T \\ E_{t-1} r_i &= E_{t-1} r_t \text{ for } i = t + 1, \dots, T. \end{aligned}$$

Thus, the change in the forward rate at the time of the announcement, i.e., $t = 1, \dots, T$, is

$$f_{s,t}^0 - f_{s,t-1}^0 = \frac{T+1-t}{T} (r_t - E_{t-1}r_t), \quad (95)$$

where $r_t - E_{t-1}r_t$ is the surprise change in the federal funds rate on day t (the day of the policy announcement). If we know the daily change in the forward rate at the time of the announcement, $f_{s,t}^0 - f_{s,t-1}^0$, then from (95) we can recover the unexpected change in the federal funds rate on the day of the FOMC announcement, t , as follows:

$$r_{t+1} - E_t r_{t+1} = \frac{T}{T-t} (f_{s,t+1}^0 - f_{s,t}^0) \text{ for } t = 0, \dots, T-1. \quad (96)$$

This condition is the same as condition (7) in Kuttner (2001), which is the convention used by the event-study literature to map the change in the 30-day federal funds futures rate on the day of the FOMC policy announcement into the surprise change in the daily policy rate on the day of the announcement. In terms of the notation for our high-frequency instrument introduced in Section B.4.1, we set $z_t = \frac{T}{T-t} (f_{s,t+1}^0 - f_{s,t}^0) \equiv i_{t,m_t^*+20} - i_{t,m_t^*-10}$, where $f_{s,t+1}^0 - f_{s,t}^0$ is measured (using high-frequency data) as the change in the 30-day federal funds futures rate over a 30-minute window around the FOMC announcement that takes place on day t .

⁶³If r_t were the actual target federal funds rate, then the assumption that it changes at most once in the month would be exactly true for most of our sample; see, e.g., footnote 16 in Gorodnichenko and Weber (2016). In general this has to be regarded as an approximation, since on any given day the effective federal funds rate, r_t , can and does deviate somewhat from the announced federal funds rate target rate (see Afonso and Lagos, 2014).

Portfolio	Turnover	beta	E-based			H-based			HFIV		
			Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.
1	-22.58		-1.90	2.36		-4.54	5.11		-5.01	3.60	
2	-13.04		-4.54**	1.97		-7.25*	4.56		-6.49**	3.39	
3	-9.83		-2.64**	1.46		-6.25*	3.98		-3.78*	2.62	
4	-7.68		-5.07***	1.59		-9.31**	4.69		-6.43***	2.62	
5	-5.99		-4.79***	1.67		-8.88**	4.61		-6.68***	2.83	
6	-4.62		-4.39***	1.21		-8.29**	3.90		-6.68***	2.52	
7	-3.42		-3.92***	1.51		-7.23**	3.94		-6.33**	2.82	
8	-2.33		-3.80***	1.24		-8.43**	4.30		-5.71***	2.32	
9	-1.31		-4.64***	1.21		-9.59***	4.12		-6.70***	2.34	
10	-0.36		-4.16***	1.13		-7.73**	3.49		-6.87***	2.41	
11	0.52		-4.26***	1.46		-7.72**	3.67		-7.79***	2.36	
12	1.44		-5.15***	1.12		-10.27***	4.08		-7.86***	2.39	
13	2.44		-5.60***	1.31		-10.79***	4.04		-9.32***	2.53	
14	3.56		-6.52***	1.41		-12.09***	4.64		-10.52***	2.85	
15	4.79		-7.09***	1.63		-11.90***	4.22		-11.89***	3.09	
16	6.20		-7.74***	1.81		-13.23***	4.67		-11.78***	3.10	
17	7.88		-6.24***	2.20		-10.57**	4.65		-11.88***	3.73	
18	10.03		-6.75***	2.09		-11.75***	4.44		-13.87***	3.48	
19	13.25		-10.33***	2.68		-17.40***	6.03		-18.80***	5.11	
20	25.04		-11.51***	3.35		-18.75***	6.21		-23.19***	5.39	

Table 4: Empirical responses of NYSE stock returns to monetary policy across portfolios sorted on return sensitivity to aggregate turnover. *** denotes significance at the 1 percent level, ** significance at the 5 percent level, * significance at the 10 percent level.

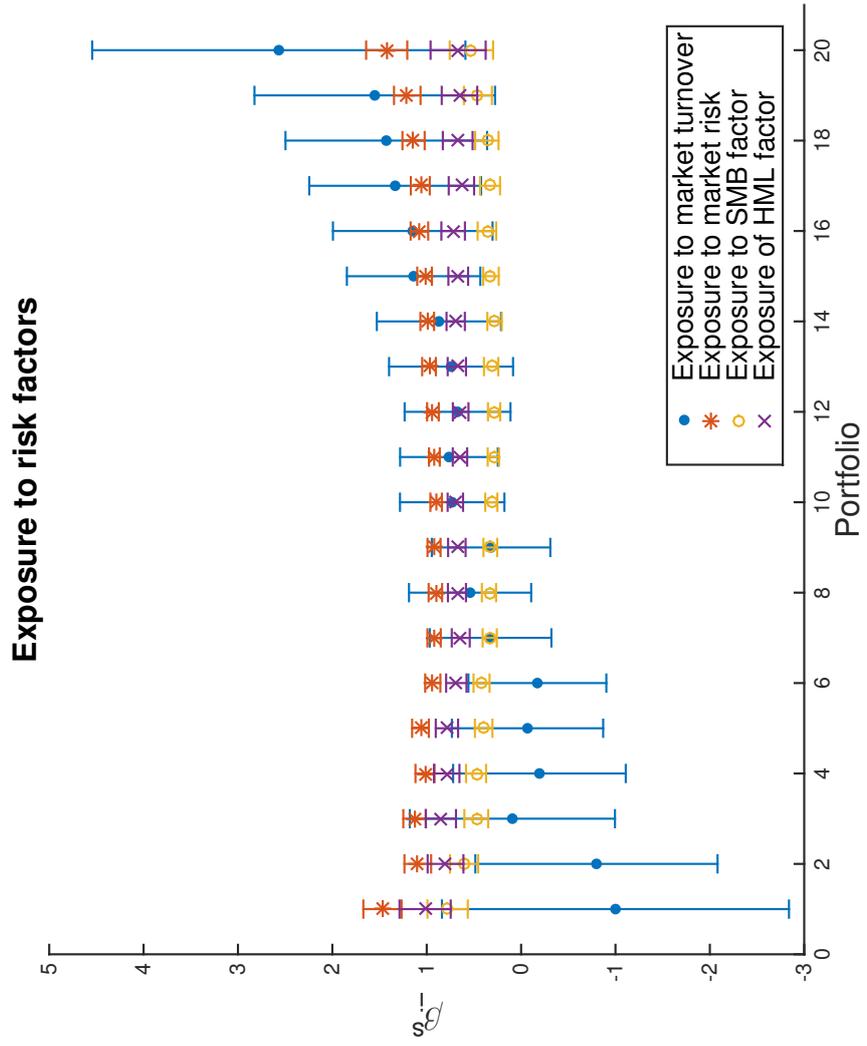


Figure 9: Betas for the 20 portfolios sorted on sensitivity of return to aggregate turnover.

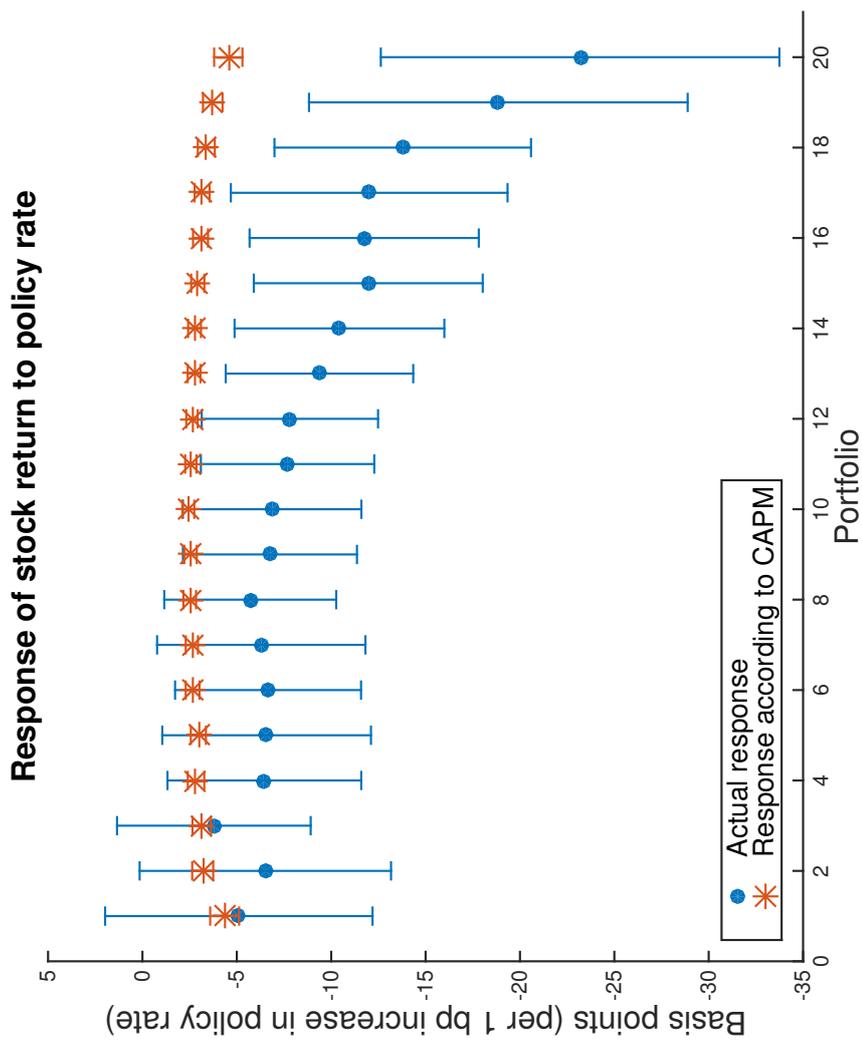


Figure 10: E-based estimates of responses of announcement-day stock returns to a 1 basis point surprise increase in the policy rate: CAPM vs. response based on portfolio analysis (for portfolios sorted on sensitivity of return to aggregate turnover).

C Supplementary material: Theory

C.1 Efficiency

Consider a social planner who wishes to maximize the sum of all agents' expected discounted utilities subject to the same meeting frictions that agents face in the decentralized formulation. Specifically, in the first subperiod of every period, the planner can only reallocate assets among all dealers and the measure α of investors who contact dealers at random. We restrict attention to symmetric allocations (identical agents receive equal treatment). Let c_{Dt} and h_{Dt} denote a dealer's consumption and production of the homogeneous consumption good in the second subperiod of period t . Let c_{It} and h_{It} denote an investor's consumption and production of the homogeneous consumption good in the second subperiod of period t . Let \tilde{a}_{Dt} denote the beginning-of-period t (before depreciation) equity holding of a dealer, and let a'_{Dt} denote the equity holding of a dealer at the end of the first subperiod of period t (after OTC trade). Let \tilde{a}_{It} denote the beginning-of-period t (before depreciation and endowment) asset holding of an investor. Finally, let a'_{It} denote a measure on $\mathcal{F}([\varepsilon_L, \varepsilon_H])$, the Borel σ -field defined on $[\varepsilon_L, \varepsilon_H]$. The measure a'_{It} is interpreted as the distribution of post-OTC-trade asset holdings among investors with different valuations who contacted a dealer in the first subperiod of period t . With this notation, the planner's problem consists of choosing a nonnegative allocation,

$$\left\{ [\tilde{a}_{jt}, a'_{jt}, c_{jt}, h_{jt}]_{j \in \{D, I\}} \right\}_{t=0}^{\infty},$$

to maximize

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\alpha \int_{\varepsilon_L}^{\varepsilon_H} \varepsilon y_t a'_{It} (d\varepsilon) + (1 - \alpha) \int_{\varepsilon_L}^{\varepsilon_H} \varepsilon y_t a_{It} dG(\varepsilon) + c_{Dt} + c_{It} - h_{Dt} - h_{It} \right]$$

(the expectation operator \mathbb{E}_0 is with respect to the probability measure induced by the dividend process) subject to

$$\tilde{a}_{Dt} + \tilde{a}_{It} \leq A^s \tag{97}$$

$$a'_{Dt} + \alpha \int_{\varepsilon_L}^{\varepsilon_H} a'_{It} (d\varepsilon) \leq a_{Dt} + \alpha a_{It} \tag{98}$$

$$c_{Dt} + c_{It} \leq h_{Dt} + h_{It} \tag{99}$$

$$a_{Dt} = \delta \tilde{a}_{Dt} \tag{100}$$

$$a_{It} = \delta \tilde{a}_{It} + (1 - \delta) A^s. \tag{101}$$

According to Proposition 11, the efficient allocation is characterized by the following two properties: (a) only dealers carry equity between periods, and (b) among those investors who have a trading opportunity with a dealer, only those with the highest valuation hold equity shares at the end of the first subperiod.

Proposition 11 *The efficient allocation satisfies the following two conditions for every t : (a) $\tilde{a}_{Dt} = A^s - \tilde{a}_{It} = A^s$ and (b) $a'_{It}(E) = \mathbb{I}_{\{\varepsilon_H \in E\}} [\delta + \alpha(1 - \delta)] A^s / \alpha$, where $\mathbb{I}_{\{\varepsilon_H \in E\}}$ is an indicator function that takes the value 1 if $\varepsilon_H \in E$, and 0 otherwise, for any $E \in \mathcal{F}([\varepsilon_L, \varepsilon_H])$.*

Proof of Proposition 11. The choice variable a'_{Dt} does not appear in the planner's objective function, so $a'_{Dt} = 0$ at an optimum. Also, (99) must bind for every t at an optimum, so the planner's problem is equivalent to

$$\begin{aligned} \max_{\{\tilde{a}_{Dt}, \tilde{a}_{It}, a'_{It}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\alpha \int_{\varepsilon_L}^{\varepsilon_H} \varepsilon a'_{It}(d\varepsilon) + (1 - \alpha) \bar{\varepsilon} \tilde{a}_{It} \right] y_t \\ \text{s.t. (97), (100), (101), and } \alpha \int_{\varepsilon_L}^{\varepsilon_H} a'_{It}(d\varepsilon) \leq a_{Dt} + \alpha a_{It}. \end{aligned}$$

Let W^* denote the maximum value of this problem. Then clearly, $W^* \leq \bar{W}^*$, where

$$\bar{W}^* = \max_{\{\tilde{a}_{Dt}, \tilde{a}_{It}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t [\varepsilon_H (\tilde{a}_{Dt} + \alpha \tilde{a}_{It}) + (1 - \alpha) \bar{\varepsilon} \tilde{a}_{It}] \delta y_t + w$$

s.t. (97), where $w \equiv [\alpha \varepsilon_H + (1 - \alpha) \bar{\varepsilon}] (1 - \delta) A^s \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t y_t$. Rearrange the expression for \bar{W}^* and substitute (97) (at equality) to obtain

$$\begin{aligned} \bar{W}^* &= \max_{\{\tilde{a}_{It}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \{ \varepsilon_H A^s - (1 - \alpha) (\varepsilon_H - \bar{\varepsilon}) \tilde{a}_{It} \} \delta y_t + w \\ &= \{ \delta \varepsilon_H + (1 - \delta) [\alpha \varepsilon_H + (1 - \alpha) \bar{\varepsilon}] \} A^s \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t y_t. \end{aligned}$$

The allocation consisting of $\tilde{a}_{Dt} = A^s$, $\tilde{a}_{It} = 0$, and the Dirac measure defined in the statement of the proposition achieve \bar{W}^* and therefore solve the planner's problem. ■

C.2 Examples

In this section we present two examples for which the basic model of Section 2 can be solved in closed form.

Example 1 Suppose that the probability distribution over investor valuations is concentrated on two points: ε_L with probability π_L and ε_H with probability π_H , with $\bar{\varepsilon} = \pi_H \varepsilon_H + \pi_L \varepsilon_L$. Then (13) implies

$$\varepsilon^* = \begin{cases} \frac{\varepsilon_H}{1 + \frac{\mu - \bar{\beta}}{\alpha\theta\bar{\beta}(1-\bar{\beta}\delta)\pi_H}} & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{\bar{\beta}\alpha\theta(1-\bar{\beta}\delta)\pi_H\varepsilon_H - (\mu - \bar{\beta})\bar{\beta}\delta(\bar{\varepsilon} - \alpha\theta\pi_L\varepsilon_L)}{\bar{\beta}\alpha\theta(1-\bar{\beta}\delta)\pi_H + (\mu - \bar{\beta})[1 - \bar{\beta}\delta(1 - \alpha\theta\pi_L)]} & \text{if } \hat{\mu} < \mu < \bar{\mu} \end{cases}$$

with

$$\hat{\mu} = \bar{\beta} \left[1 + \frac{(1 - \bar{\beta}\delta)(1 - \alpha\theta)\alpha\theta\pi_L(\bar{\varepsilon} - \varepsilon_L)}{\bar{\varepsilon} - \alpha\theta\pi_L\varepsilon_L} \right] \quad \text{and} \quad \bar{\mu} = \bar{\beta} \left[1 + \frac{(1 - \bar{\beta}\delta)\alpha\theta(\bar{\varepsilon} - \varepsilon_L)}{\bar{\beta}\delta\bar{\varepsilon} + (1 - \bar{\beta}\delta)\varepsilon_L} \right].$$

Given ε^* , the closed-form expressions for the equilibrium allocation are given in Proposition 1.

Example 2 Suppose that the probability distribution over investor valuations is distributed uniformly on $[0, 1]$. Then (13) implies

$$\varepsilon^* = \begin{cases} \frac{\alpha\theta(1-\bar{\beta}\delta) + \iota - \sqrt{[\alpha\theta(1-\bar{\beta}\delta) + \iota]^2 - [\alpha\theta(1-\bar{\beta}\delta)]^2}}{\alpha\theta(1-\bar{\beta}\delta)} & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{(1-\bar{\beta}\delta)(\alpha\theta + \iota) - \sqrt{[(1-\bar{\beta}\delta)(\alpha\theta + \iota)]^2 - \alpha\theta\bar{\beta}\delta[1-\bar{\beta}\delta(1+\iota)](\bar{\iota} - \iota)}}{\alpha\theta[1-\bar{\beta}\delta(1+\iota)]} & \text{if } \hat{\mu} < \mu < \bar{\mu} \end{cases}$$

with

$$\hat{\mu} = \bar{\beta} \left[1 + \frac{(1 - \bar{\beta}\delta)(1 - \alpha\theta)(\hat{\varepsilon} - 1/2)}{\hat{\varepsilon}} \right] \quad \text{and} \quad \bar{\mu} = \bar{\beta} \left[1 + \frac{\alpha\theta(1 - \bar{\beta}\delta)}{\bar{\beta}\delta} \right]$$

and where $\bar{\iota} \equiv (\bar{\mu} - \bar{\beta})/\bar{\beta}$ and $\hat{\varepsilon} = (1 - \sqrt{1 - \alpha\theta})/(\alpha\theta)$. Given ε^* , the closed-form expressions for the equilibrium allocation are given in Proposition 1.

C.3 Equilibrium conditions for the general model

In this section we derive the equilibrium conditions for the general model of Section 6. We specialize the analysis to recursive equilibria in which prices are time-invariant functions of an aggregate state vector that follows a time-invariant law of motion. The state vector is $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_t) \in \mathbb{R}_+^5$, with $\boldsymbol{\tau}_t \equiv (\omega_t, \mu_t, r_t)$. Asset prices in a recursive equilibrium will be $\phi_t^s = \phi^s(\mathbf{x}_t)$, $\bar{\phi}_t^s = \bar{\phi}^s(\mathbf{x}_t)$, $\phi_t^m = \phi^m(\mathbf{x}_t)$, $p_t^s = p^s(\mathbf{x}_t)$, $q_t = q(\mathbf{x}_t)$, and $\varepsilon_t^{s*} = \varepsilon^{s*}(\mathbf{x}_t)$. Let A_t^{mk} denote the amount of money that investors have available to trade asset $k \in \bar{\mathbb{N}} \equiv \mathbb{N} \cup \{b\}$ at the beginning of period t (i.e., the bond, if $k = b$, and equity, if $k \in \mathbb{N}$). The laws of motion for the state variables A_t^m , y_t , and $\boldsymbol{\tau}_t$ are exogenous (as described above) while $A_t^{mk} = \Psi^k(\mathbf{x}_t)$, where the decision rule Ψ^k , for $k \in \bar{\mathbb{N}}$, is determined in equilibrium.

The investor's value functions are

$$W^I(a_t^{mb}, a_t^b, (a_t^{ms}, a_t^s)_{s \in \mathbb{N}}, k_t; \mathbf{x}_t) = \sum_{s \in \mathbb{N}} [\phi^m(\mathbf{x}_t) a_t^{ms} + \phi^s(\mathbf{x}_t) a_t^s] \\ + \phi^m(\mathbf{x}_t) (a_t^{mb} + a_t^b) - k_t + \bar{W}^I(\mathbf{x}_t),$$

where a_t^b denotes the quantity of bonds that the investor brings into the second subperiod of period t , with

$$\bar{W}^I(\mathbf{x}_t) \equiv T(\mathbf{x}_t) + \max_{(\tilde{a}_{t+1}^m, (\tilde{a}_{t+1}^s)_{s \in \mathbb{N}}) \in \mathbb{R}_+^{N+1}} \left\{ -\phi^m(\mathbf{x}_t) \tilde{a}_{t+1}^m - \sum_{s \in \mathbb{N}} \phi^s(\mathbf{x}_t) \tilde{a}_{t+1}^s \right. \\ \left. + \frac{1}{1+r_t} \mathbb{E} \left[\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1}) \mid \mathbf{x}_t \right] \right\}, \\ \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1}) = \max_{(a_{t+1}^{mk})_{k \in \bar{\mathbb{N}}} \in \mathbb{R}_+^{N+1}} \int V^I(a_{t+1}^{mb}, (a_{t+1}^{ms}, a_{t+1}^s)_{s \in \mathbb{N}}, \varepsilon; \mathbf{x}_{t+1}) dG(\varepsilon) \quad (102) \\ \text{s.t. } \sum_{k \in \bar{\mathbb{N}}} a_{t+1}^{mk} \leq \tilde{a}_{t+1}^m,$$

and

$$V^I(a_{t+1}^{mb}, (a_{t+1}^{ms}, a_{t+1}^s)_{s \in \mathbb{N}}, \varepsilon; \mathbf{x}_{t+1}) = \phi^m(\mathbf{x}_{t+1}) \{a_{t+1}^{mb} + [1 - q(\mathbf{x}_{t+1})] a_{t+1}^b(a_{t+1}^{mb}, q(\mathbf{x}_{t+1}))\} \\ + \sum_{s \in \mathbb{N}} \{ \phi^m(\mathbf{x}_{t+1}) a_{t+1}^{ms} + [\varepsilon y_{t+1} + \phi^s(\mathbf{x}_{t+1})] a_{t+1}^s \} \\ + \sum_{s \in \mathbb{N}} \left[\alpha^s \theta \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} \mathbb{I}_{\{\varepsilon^{s*}(\mathbf{x}_{t+1}) < \varepsilon\}} a_{t+1}^{ms} \right] \\ + \sum_{s \in \mathbb{N}} \{ \alpha^s \theta [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} \mathbb{I}_{\{\varepsilon < \varepsilon^{s*}(\mathbf{x}_{t+1})\}} a_{t+1}^s \} \\ + \bar{W}^I(\mathbf{x}_{t+1}),$$

where $a_t^b(a_t^{mb}, q_t)$ is the bond demand of an agent who carries a_t^{mb} dollars into the bond market in state \mathbf{x}_t , and $a_{t+1}^s \equiv \delta \tilde{a}_{t+1}^s + (1 - \delta) A^s$. In writing $V^I(\cdot)$ we have used the fact that Lemma 1 still characterizes the equilibrium post-trade portfolios in the OTC market. The following lemma characterizes an investor's demand in the bond market.

Lemma 5 *Consider an investor who brings a_t^{mb} dollars to the bond market of period t . The bond demand, $a_t^b(a_t^{mb}, q_t)$ and the post-trade bond-market cash holdings, $\bar{a}_t^{mb}(a_t^{mb}, q_t) = a_t^{mb} -$*

$q_t a_t^b(a_t^{mb}, q_t)$, are given by

$$\begin{aligned} a_t^b(a_t^{mb}, q_t) &= \chi(q_t, 1) \frac{a_t^{mb}}{q_t} \\ \bar{a}_t^{mb}(a_t^{mb}, q_t) &= [1 - \chi(q_t, 1)] a_t^{mb}, \end{aligned}$$

where $\chi(\cdot, \cdot)$ is the function defined in Lemma 1.

Proof. The investor's problem in the bond market of period t is

$$\max_{(\bar{a}_t^{mb}, a_t^b) \in \mathbb{R}_+^2} W^I(\bar{a}_t^{mb}, a_t^b, (a_t^{ms}, a_t^s)_{s \in \mathbb{N}}, k_t; \mathbf{x}_t) \text{ s.t. } \bar{a}_t^{mb} + q_t a_t^b \leq a_t^{mb}.$$

This problem can be written as

$$\max_{a_t^b \in [0, a_t^{mb}/q_t]} \phi^m(\mathbf{x}_t) \left[(a_t^{mb} + (1 - q_t) a_t^b) \right] + W^I((a_t^{ms}, a_t^s)_{s \in \mathbb{N}}, 0, 0, k_t; \mathbf{x}_t),$$

and the solution is as in the statement of the lemma. ■

The market-clearing condition for bonds is $a_t^b(A_t^{mb}, q_t) = B_t$, which implies the equilibrium nominal price of a bond is $q_t = \min(A_t^{mb}/B_t, 1)$, or in the recursive equilibrium,

$$q(\mathbf{x}_t) = \min \left\{ \frac{\Psi^b(\mathbf{x}_t)}{\omega_t A_t^m}, 1 \right\}.$$

With Lemma 5, the investor's value function in the first subperiod becomes

$$\begin{aligned} V^I(a_{t+1}^{mb}, (a_{t+1}^{ms}, a_{t+1}^s)_{s \in \mathbb{N}}, \varepsilon; \mathbf{x}_{t+1}) &= \frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} a_{t+1}^{mb} + \bar{W}^I(\mathbf{x}_{t+1}) \\ &+ \sum_{s \in \mathbb{N}} \{ \phi^m(\mathbf{x}_{t+1}) a_{t+1}^{ms} + [\varepsilon y_{t+1} + \phi^s(\mathbf{x}_{t+1})] a_{t+1}^s \} \\ &+ \sum_{s \in \mathbb{N}} \alpha^s \theta \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} \mathbb{I}_{\{\varepsilon^{s*}(\mathbf{x}_{t+1}) < \varepsilon\}} a_{t+1}^{ms} \\ &+ \sum_{s \in \mathbb{N}} \alpha^s \theta [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} \mathbb{I}_{\{\varepsilon < \varepsilon^{s*}(\mathbf{x}_{t+1})\}} a_{t+1}^s. \end{aligned}$$

The following lemma characterizes the optimal partition of money across asset classes chosen by an investor at the beginning of the period.

Lemma 6 *The $(a_{t+1}^{mk})_{k \in \bar{\mathbb{N}}}$ that solves (102) satisfies*

$$\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \geq \phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) \quad (103)$$

$$\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \geq \frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})}, \quad (104)$$

where (103) holds with “=” if $a_{t+1}^{ms} > 0$ and (104) holds with “=” if $a_{t+1}^{mb} > 0$.

Proof. The objective function on the right side of (102) can be written as

$$\begin{aligned}
& \int V^I(a_{t+1}^{mb}, (a_{t+1}^{ms}, a_{t+1}^s)_{s \in \mathbb{N}}, \varepsilon; \mathbf{x}_{t+1}) dG(\varepsilon) \\
&= \sum_{s \in \mathbb{N}} \left\{ \phi^m(\mathbf{x}_{t+1}) a_{t+1}^{ms} + [\bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1})] a_{t+1}^s \right\} \\
&+ \sum_{s \in \mathbb{N}} \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) a_{t+1}^{ms} \\
&+ \sum_{s \in \mathbb{N}} \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) a_{t+1}^s \\
&+ \frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} a_{t+1}^{mb} + \bar{W}^I(\mathbf{x}_{t+1}).
\end{aligned}$$

The Lagrangian for the maximization in (102) is

$$\begin{aligned}
\hat{\mathcal{L}}((a_{t+1}^{ms})_{s \in \mathbb{N}}; \tilde{a}_{t+1}^m, \mathbf{x}_{t+1}) &= \sum_{s \in \mathbb{N}} \left[\phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) \right] a_{t+1}^{ms} \\
&+ \frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} a_{t+1}^{mb} + \sum_{k \in \mathbb{N}} \zeta^{mk}(\mathbf{x}_{t+1}) a_{t+1}^{mk} + \xi(\mathbf{x}_{t+1}) \left(\tilde{a}_{t+1}^m - \sum_{k \in \mathbb{N}} a_{t+1}^{mk} \right),
\end{aligned}$$

where $\xi(\mathbf{x}_{t+1})$ is the multiplier on the feasibility constraint in state \mathbf{x}_{t+1} and $(\zeta^{mk}(\mathbf{x}_{t+1}))_{k \in \mathbb{N}}$ are the multipliers on the nonnegativity constraints. The first-order conditions are

$$\begin{aligned}
& \frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} + \zeta^{mb}(\mathbf{x}_{t+1}) - \xi(\mathbf{x}_{t+1}) = 0 \\
& \phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) + \zeta^{ms}(\mathbf{x}_{t+1}) - \xi(\mathbf{x}_{t+1}) = 0,
\end{aligned}$$

for all $s \in \mathbb{N}$. Finally, notice that $\xi(\mathbf{x}_{t+1}) = \partial \hat{\mathcal{L}} / \partial \tilde{a}_{t+1}^m = \partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1}) / \partial \tilde{a}_{t+1}^m$. ■

The following lemma characterizes an investor's optimal portfolio choice in the second subperiod of any period with state \mathbf{x}_t .

Lemma 7 *The portfolio $(\tilde{a}_{t+1}^m, (\tilde{a}_{t+1}^s)_{s \in \mathbb{N}})$ chosen by an investor in the second subperiod of period t with state \mathbf{x}_t of a recursive equilibrium, satisfies*

$$\begin{aligned}
\phi^s(\mathbf{x}_t) &\geq \frac{\delta}{1+r_t} \mathbb{E} \left[\bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \middle| \mathbf{x}_t \right] \\
\phi^m(\mathbf{x}_t) &\geq \frac{1}{1+r_t} \mathbb{E} \left[\phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) \middle| \mathbf{x}_t \right] \\
\phi^m(\mathbf{x}_t) &\geq \frac{1}{1+r_t} \mathbb{E} \left[\frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} \middle| \mathbf{x}_t \right],
\end{aligned}$$

where the first condition holds with “=” if $\tilde{a}_{t+1}^s > 0$, the second condition holds with “=” if $a_{t+1}^{ms} > 0$, and the third condition holds with “=” if $a_{t+1}^{mb} > 0$.

Proof. The investor’s maximization problem in the second subperiod is

$$\max_{(\tilde{a}_{t+1}^m, (\tilde{a}_{t+1}^s)_{s \in \mathbb{N}}) \in \mathbb{R}_+^{N+1}} \left\{ -\phi^m(\mathbf{x}_t) \tilde{a}_{t+1}^m - \sum_{s \in \mathbb{N}} \phi^s(\mathbf{x}_t) \tilde{a}_{t+1}^s + \frac{1}{1+r_t} \mathbb{E} \left[\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1}) \mid \mathbf{x}_t \right] \right\},$$

with

$$\begin{aligned} & \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1}) \\ &= \bar{W}^I(\mathbf{x}_{t+1}) + \max_{\{a_{t+1}^{mk}\}_{k \in \bar{\mathbb{N}}} \in \mathbb{R}_+^{N+1}} \hat{\mathcal{L}}((a_{t+1}^{ms})_{s \in \bar{\mathbb{N}}}; \tilde{a}_{t+1}^m, \mathbf{x}_{t+1}) \\ &+ \sum_{s \in \mathbb{N}} \left[\bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \right] a_{t+1}^s, \end{aligned}$$

where $\hat{\mathcal{L}}((a_{t+1}^{ms})_{s \in \bar{\mathbb{N}}}; \tilde{a}_{t+1}^m, \mathbf{x}_{t+1})$ is defined in the proof of Lemma 6. We then have,

$$\begin{aligned} \frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} &= \bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \\ \frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} &= \xi(\mathbf{x}_{t+1}). \end{aligned}$$

The first-order conditions for the investor’s optimization problem in the second subperiod are

$$\begin{aligned} -\phi^m(\mathbf{x}_t) + \frac{1}{1+r_t} \mathbb{E} \left[\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \mid \mathbf{x}_t \right] &\leq 0, \text{ with “=” if } \tilde{a}_{t+1}^m > 0 \\ -\phi^s(\mathbf{x}_t) + \frac{1}{1+r_t} \mathbb{E} \left[\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s \in \mathbb{N}}; \mathbf{x}_{t+1})}{\partial \tilde{a}_{t+1}^s} \mid \mathbf{x}_t \right] &\leq 0, \text{ with “=” if } \tilde{a}_{t+1}^s > 0, \end{aligned}$$

or equivalently,

$$\begin{aligned} \phi^m(\mathbf{x}_t) &\geq \frac{1}{1+r_t} \mathbb{E} [\xi(\mathbf{x}_{t+1}) \mid \mathbf{x}_t], \text{ with “=” if } \tilde{a}_{t+1}^m > 0 \\ \phi^s(\mathbf{x}_t) &\geq \frac{\delta}{1+r_t} \mathbb{E} \left[\bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \mid \mathbf{x}_t \right], \end{aligned}$$

with “=” if $\tilde{a}_{t+1}^s > 0$, for $s \in \mathbb{N}$. By Lemma 6, the first condition can be written as

$$\phi^m(\mathbf{x}_t) \geq \frac{1}{1+r_t} \mathbb{E} \left[\frac{\phi^m(\mathbf{x}_{t+1})}{q(\mathbf{x}_{t+1})} \mid \mathbf{x}_t \right],$$

with “=” if $a_{t+1}^{mb} > 0$, or as

$$\phi^m(\mathbf{x}_t) \geq \frac{1}{1+r_t} \mathbb{E} \left[\phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) \middle| \mathbf{x}_t \right],$$

with “=” if $a_{t+1}^{ms} > 0$, for $s \in \bar{\mathbb{N}}$. ■

Definition 2 A recursive monetary equilibrium for the multiple asset economy with open-market operations (in which only investors can hold assets overnight) is a collection of functions, $\{\phi^m(\cdot), q(\cdot), \Psi^b(\cdot), \{\phi^s(\cdot), p^s(\cdot), \varepsilon^{s*}(\cdot), \Psi^s(\cdot)\}_{s \in \bar{\mathbb{N}}}\}$, that satisfy

$$\begin{aligned} \phi^s(\mathbf{x}_t) &= \frac{\delta}{1+r_t} \mathbb{E} \left[\bar{\varepsilon} y_{t+1} + \phi^s(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\mathbf{x}_{t+1})} [\varepsilon^{s*}(\mathbf{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \middle| \mathbf{x}_t \right] \\ \phi^m(\mathbf{x}_t) &= \frac{1}{1+r_t} \mathbb{E} \left[\phi^m(\mathbf{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_{t+1})}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_{t+1})}{p^s(\mathbf{x}_{t+1})} y_{t+1} dG(\varepsilon) \middle| \mathbf{x}_t \right] \\ \frac{\phi^m(\mathbf{x}_t)}{q(\mathbf{x}_t)} &= \phi^m(\mathbf{x}_t) + \alpha^s \theta \int_{\varepsilon^{s*}(\mathbf{x}_t)}^{\varepsilon^H} \frac{\varepsilon - \varepsilon^{s*}(\mathbf{x}_t)}{p^s(\mathbf{x}_t)} y_t dG(\varepsilon) \\ q(\mathbf{x}_t) &= \min[A_t^{mb}/(\omega_t A_t^m), 1] \\ p^s(\mathbf{x}_t) &= \frac{[1 - G(\varepsilon^{s*}(\mathbf{x}_t))] A_t^{ms}}{G(\varepsilon^{s*}(\mathbf{x}_t)) A^s} \\ \varepsilon^{s*}(\mathbf{x}_t) &= \frac{p^s(\mathbf{x}_t) \phi^m(\mathbf{x}_t) - \phi^s(\mathbf{x}_t)}{y_t} \\ A_t^{mk} &= \Psi^k(\mathbf{x}_t), \text{ for } k \in \bar{\mathbb{N}} \\ A_t^m &= \sum_{k \in \bar{\mathbb{N}}} A_t^{mk}. \end{aligned}$$

Suppose $\mathbf{x}_t = (A_t^m, y_t, \omega_i, \mu_i, r_i)$ and focus on a recursive equilibrium with the property that real prices are linear functions of the aggregate dividend. Then, under the conjecture

$$\phi^s(\mathbf{x}_t) = \phi_i^s y_t \tag{105}$$

$$\bar{\phi}^s(\mathbf{x}_t) = \bar{\phi}_i^s y_t \tag{106}$$

$$\phi^m(\mathbf{x}_t) A_t^m = Z_i y_t \tag{107}$$

$$A_t^{mk} = \Psi^k(\mathbf{x}_t) = \lambda_i^k A_t^m \tag{108}$$

$$\bar{\phi}^s(\mathbf{x}_t) \equiv p^s(\mathbf{x}_t) \phi^m(\mathbf{x}_t) \tag{109}$$

$$q(\mathbf{x}_t) = \min(\lambda_i^b/\omega_i, 1) \equiv q_i \tag{110}$$

$$\varepsilon^{s*}(\mathbf{x}_t) \equiv \frac{\bar{\phi}^s(\mathbf{x}_t) - \phi^s(\mathbf{x}_t)}{y_t} = \bar{\phi}_i^s - \phi_i^s \equiv \varepsilon_i^{s*}, \tag{111}$$

the equilibrium conditions reduce to (21)-(25), which is a system of $M(3N + 2)$ independent equations to be solved for the $M(3N + 2)$ unknowns $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s, \lambda_i^b\}_{i \in \mathbb{M}, s \in \mathbb{N}}$. Given $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s, \lambda_i^b\}_{i \in \mathbb{M}, s \in \mathbb{N}}$, for a state $\mathbf{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_t)$ with $\boldsymbol{\tau}_t = \boldsymbol{\tau}_i = (\omega_i, \mu_i, r_i)$, $\phi^s(\mathbf{x}_t)$ is obtained from (105), $\bar{\phi}^s(\mathbf{x}_t)$ from (106) (with $\bar{\phi}_i^s = \varepsilon_i^{s*} + \phi_i^s$), $\phi^m(\mathbf{x}_t)$ from (107), A_t^{mk} from (108), $p^s(\mathbf{x}_t)$ from (109), and $q(\mathbf{x}_t)$ from (110). Notice that an economy with no explicit open-market operations is just special case of this economy with $\omega_t = 0$ for all t (which in turn implies $\lambda_i^b = 0$ for all i , so (23) is dropped from the set of equilibrium conditions).

The following proposition shows that if a monetary equilibrium exists for a given joint policy process for money growth and real rates, $\{\mu_t, r_t\}_{t=0}^\infty$, then there exists a bond policy, $\{\omega_t\}_{t=0}^\infty$ that implements a positive real value of money that is constant over time. This result is useful because it implies the real price of money need not change at the times when monetary policy switches states.

Proposition 12 *Let $\langle (\mu_i, r_i), [\sigma_{ij}] \rangle_{i,j \in \mathbb{M}}$ denote a (Markov chain for the) joint process of money growth and real rates, i.e., a set of states $(\mu_i, r_i)_{i \in \mathbb{M}}$ and a transition matrix $[\sigma_{ij}]_{i,j \in \mathbb{M}}$ such that $\sigma_{ij} = \Pr[(\mu_{t+1}, r_{t+1}) = (\mu_j, r_j) \mid (\mu_t, r_t) = (\mu_i, r_i)]$. Consider a process $\langle (\mu_i, r_i), [\sigma_{ij}] \rangle_{i,j \in \mathbb{M}}$ such that there exists a vector $(\phi_i^s, \varepsilon_i^{s*})_{i \in \mathbb{M}, s \in \mathbb{N}}$ that solves*

$$\phi_i^s = \frac{\bar{\gamma}\delta}{1 + r_i} \sum_{j \in \mathbb{M}} \sigma_{ij} \left[\bar{\varepsilon} + \phi_j^s + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon_j^{s*}} (\varepsilon_j^{s*} - \varepsilon) dG(\varepsilon) \right] \text{ for } (i, s) \in \mathbb{M} \times \mathbb{N} \quad (112)$$

$$1 = \frac{\bar{\gamma}}{(1 + r_i) \mu_i} \sum_{j \in \mathbb{M}} \sigma_{ij} \left[1 + \alpha^s \theta \int_{\varepsilon_j^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_j^{s*}}{\varepsilon_j^{s*} + \phi_j^s} dG(\varepsilon) \right] \text{ for } (i, s) \in \mathbb{M} \times \mathbb{N}. \quad (113)$$

Then for any $Z \in (Z_0, \infty)$, there exists a bond policy $(\omega_i)_{i \in \mathbb{M}}$ that implements equilibrium aggregate real balances $(Z_i)_{i \in \mathbb{M}}$ with $Z_i = Z$ for all $i \in \mathbb{M}$. Moreover, the bond policy that implements the constant aggregate real balance Z is

$$\omega_i = \left[1 - \frac{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon_i^{s*}) A^s}{1 - G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)}{Z} \right] \left[1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon) \right] \text{ for } i \in \mathbb{M}, \quad (114)$$

and

$$Z_0 = \max_{i \in \mathbb{N}} \sum_{s \in \mathbb{N}} \frac{G(\varepsilon_i^{s*}) A^s}{1 - G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s).$$

Under bond policy (114), in state $\mathbf{x}_t = (A_t^m, y_t, \omega_i, \mu_i, r_i)$, investors assign $\lambda_i^b Z$ real balances to

the bond market and $\lambda_i^s Z$ real balances to the market for stock $s \in \mathbb{N}$, where

$$\lambda_i^b = 1 - \frac{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon_i^{s*}) A^s}{1-G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)}{Z} \in (0, 1) \quad (115)$$

$$\lambda_i^s = \frac{\frac{G(\varepsilon_i^{s*}) A^s}{1-G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)}{Z} \in (0, 1), \quad (116)$$

and the dollar price of equity in the OTC round is $p^s(\mathbf{x}_t) = (\varepsilon_i^{s*} + \phi_i^s) A_t^m / Z$.

Proof. Given the vector $(\phi_i^s, \varepsilon_i^{s*})_{i \in \mathbb{M}, s \in \mathbb{N}}$ that solves (112) and (113), (23)-(25) imply

$$Z = \frac{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon_i^{s*}) A^s}{1-G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)}{1 - \frac{\omega_i}{1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon)}} \quad (117)$$

$$\lambda_i^b = \frac{\omega_i}{1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon)} \quad (118)$$

$$\lambda_i^s = \left[1 - \frac{\omega_i}{1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon)} \right] \frac{\frac{G(\varepsilon_i^{s*}) A^s}{1-G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)}{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon_i^{s*}) A^s}{1-G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s)} \quad (119)$$

From (117), it is clear that the bond policy $(\omega_i)_{i \in \mathbb{M}}$ described in the proposition implements aggregate real balance Z . Then (118) and (119) imply (115) and (116), and $\lambda_i^b, \lambda_i^s \in (0, 1)$ since $0 < Z_0 < Z$. Finally, $p^s(\mathbf{x}_t)$ is obtained from (109). ■

In general, the equilibrium for the general model with N asset classes, open-market operations, and policy uncertainty, involves numerically solving the system of $M(3N + 2)$ independent equations and $M(3N + 2)$ unknowns given by (21)-(25). In order to gain analytical intuition, the following proposition offers a full characterization of the monetary equilibrium for an economy with N equity classes and open-market operations, but no policy uncertainty. In this context, Corollary 5 deals with implementing a level of real balance that is independent of the growth rate of the money supply.

Proposition 13 *Consider the economy with no policy uncertainty, i.e., $\mu_i = \mu$, $\omega_i = \omega$, and $r_i = r$ for all $i \in \mathbb{M}$. Let $\bar{\mu}^s \equiv \bar{\beta} \left[1 + \frac{\alpha^s \theta (1 - \bar{\beta} \delta) (\bar{\varepsilon} - \varepsilon_L)}{\bar{\beta} \delta \bar{\varepsilon} + (1 - \bar{\beta} \delta) \varepsilon_L} \right]$ and $\bar{\mu}^* = \min_{s \in \mathbb{N}} \bar{\mu}^s$, and assume $\mu \in (\bar{\beta}, \bar{\mu}^*)$ and $\omega \in (0, \mu / \bar{\beta})$. Then there exists a unique recursive monetary equilibrium:*

(i) Asset prices are

$$\phi_t^s = \phi^s y_t,$$

where

$$\phi^s = \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}} (\varepsilon^{s*} - \varepsilon) dG(\varepsilon) \right] \quad (120)$$

and $\varepsilon^{s*} \in (\varepsilon_L, \varepsilon_H)$ is the unique solution to

$$\frac{\int_{\varepsilon^{s*}}^{\varepsilon_H} (\varepsilon - \varepsilon^{s*}) dG(\varepsilon)}{\varepsilon^{s*} + \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta} \left[\bar{\varepsilon} + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}} (\varepsilon^{s*} - \varepsilon) dG(\varepsilon) \right]} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha^s \theta} = 0. \quad (121)$$

(ii) Aggregate real balances are

$$\phi_t^m A_t^m = Z y_t,$$

where

$$Z = \frac{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon^{s*}) A^s}{1 - G(\varepsilon^{s*})} (\varepsilon^{s*} + \phi^s)}{1 - \frac{\bar{\beta}}{\mu} \omega}. \quad (122)$$

(iii) The price of a bond is

$$q_t = \frac{\bar{\beta}}{\mu}. \quad (123)$$

(iv) The proportion of real balances assigned to the bond market is

$$\lambda^b = \frac{\bar{\beta}}{\mu} \omega. \quad (124)$$

(v) The proportion of real balances assigned to the OTC market for equity s is

$$\lambda^s = \frac{\frac{G(\varepsilon^{s*}) A^s}{1 - G(\varepsilon^{s*})} (\varepsilon^{s*} + \phi^s)}{\sum_{s \in \mathbb{N}} \frac{G(\varepsilon^{s*}) A^s}{1 - G(\varepsilon^{s*})} (\varepsilon^{s*} + \phi^s)} \left(1 - \frac{\bar{\beta}}{\mu} \omega \right). \quad (125)$$

Proof. With no policy uncertainty, $\phi_i^s = \phi^s$, $\varepsilon_i^{s*} = \varepsilon^{s*}$, $Z_i = Z$, $\lambda_i^s = \lambda^s$, $\lambda_i^b = \lambda^b$ for all

$i \in \mathbb{M}$ and all $s \in \mathbb{N}$, and the equilibrium conditions (21)-(25) reduce to

$$\phi^s = \bar{\beta}\delta \left[\bar{\varepsilon} + \phi^s + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon^{s*}} (\varepsilon^{s*} - \varepsilon) dG(\varepsilon) \right] \text{ for all } s \in \mathbb{N} \quad (126)$$

$$1 = \frac{\bar{\beta}}{\mu} \left[1 + \alpha^s \theta \int_{\varepsilon^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}}{\varepsilon^{s*} + \phi^s} dG(\varepsilon) \right] \text{ for all } s \in \mathbb{N} \quad (127)$$

$$\max(\omega/\lambda^b, 1) = 1 + \alpha^s \theta \int_{\varepsilon^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}}{\varepsilon^{s*} + \phi^s} dG(\varepsilon) \text{ for all } s \in \mathbb{N} \quad (128)$$

$$Z\lambda^s = \frac{G(\varepsilon^{s*}) A^s}{1 - G(\varepsilon^{s*})} (\varepsilon^{s*} + \phi^s) \text{ for all } s \in \mathbb{N} \quad (129)$$

$$1 - \lambda^b = \sum_{s \in \mathbb{N}} \lambda^s. \quad (130)$$

This is a system of $3N+2$ independent equations in the $3N+2$ unknowns, $\{\{\phi^s, \varepsilon^{s*}, \lambda^s\}_{s \in \mathbb{N}}, \lambda^b, Z\}$. Conditions (126) and (127) imply (120) and (121). It is easy to check there exists a unique $\varepsilon^{s*} \in (\varepsilon_L, \varepsilon_H)$ provided $\mu \in (\bar{\beta}, \bar{\mu}^s)$. Given $\{\phi^s, \varepsilon^{s*}\}_{s \in \mathbb{N}}$, conditions (128)-(130) need to be solved for $\{\{\lambda^s\}_{s \in \mathbb{N}}, \lambda^b, Z\}$. Conditions (129) imply the values of $\{Z\lambda^s\}_{s \in \mathbb{N}}$. Conditions (127) and (128) imply $\max(\omega/\lambda^b, 1) = \mu/\bar{\beta}$, and since $\bar{\beta} < \mu$, this implies (123) and (124). Finally, condition (130) implies (122) and therefore (129) implies (125). ■

Corollary 5 Consider the economy of Proposition 13. Let $\{\varepsilon^{s*}(\mu), \phi^s(\mu)\}_{s \in \mathbb{N}}$ denote the vector $\{\varepsilon^{s*}, \phi^s\}_{s \in \mathbb{N}}$ that solves (120) and (121) for a given μ , and let

$$\mathcal{Z}(\mu) \equiv \sum_{s \in \mathbb{N}} \frac{G[\varepsilon^{s*}(\mu)] A^s}{1 - G[\varepsilon^{s*}(\mu)]} [\varepsilon^{s*}(\mu) + \phi^s(\mu)].$$

(i) The monetary authority can implement any real balance $Z \in [0, \infty)$.

(ii) For any $\mu_0 \in (\bar{\beta}, \bar{\mu}^*)$, any equilibrium aggregate real balance $Z \in (Z_0, \infty)$, where $Z_0 = \mathcal{Z}(\mu_0)$, can be implemented in a way that it is independent of the money growth rate, μ , for any $\mu \in (\mu_0, \bar{\mu}^*)$.

(iii) Any equilibrium aggregate real balance $Z_0 \in (0, \infty)$ can be implemented independently of the money growth rate, μ , provided $\mu \in (\mu_0, \bar{\mu}^*)$, where μ_0 is the unique solution to $\mathcal{Z}(\mu_0) = Z_0$.

Proof. (i) Fix ω . From (121), it is clear that by varying μ in the interval $(\bar{\beta}, \bar{\mu}^*)$, the monetary authority can implement $\varepsilon^{s*} = \varepsilon_L$, as well as $\varepsilon^{s*} = \varepsilon_H$ for all $s \in \mathbb{N}$. The result then follows from (122).

(ii) Fix $\mu_0 \in (\bar{\beta}, \bar{\mu}^*)$ and let $Z_0 = \mathcal{Z}(\mu_0)$. Then for any $Z \in (Z_0, \infty)$, set

$$\omega = \left(1 - \frac{\mathcal{Z}(\mu)}{Z}\right) \frac{\mu}{\bar{\beta}}. \quad (131)$$

Clearly, $\omega \in (0, \mu/\bar{\beta})$ for any $\mu \in (\mu_0, \bar{\mu}^*)$. To conclude, notice that for any $\mu \in (\mu_0, \bar{\mu}^*)$, the bond policy (131) implements the constant aggregate real balance Z .

(iii) Fix $Z_0 \in (0, \infty)$ and let μ_0 denote the unique solution to $\mathcal{Z}(\mu_0) = Z_0$. Then for any $\mu \in (\mu_0, \bar{\mu}^*)$, set

$$\omega = \left(1 - \frac{\mathcal{Z}(\mu)}{Z_0}\right) \frac{\mu}{\bar{\beta}}. \quad (132)$$

Clearly, $\omega \in (0, \mu/\bar{\beta})$ for any $\mu \in (\mu_0, \bar{\mu}^*)$, and the bond policy (132) implements the constant aggregate real balance Z_0 . ■

D Supplementary material: Robustness

In this section we perform several robustness checks on the empirical and quantitative analyses.

D.1 Delayed return response

Our quantitative theory predicts that returns of more liquid stocks are more responsive than returns of less liquid stocks to monetary policy shocks on the announcement day, and that these differences persist beyond the announcement day. The prediction for announcement days is in line with the empirical estimations we have carried out in Section 5.2 and Section 5.3. However, the evidence in those sections may also be consistent with an alternative hypothesis, namely, that while the more liquid stocks may experience a stronger reaction than less liquid stocks on the day of the announcement, this differential response would dissipate if we gave the less liquid stocks more time to react. We have already pointed out (see footnote 37) that this hypothesis is at odds with the VAR evidence in Section 5.4. In this section we redo the estimations in Section 5.2 and Section 5.3 by looking at two-day cumulative returns after the announcement, and find no support for the alternative hypothesis.

For $j = 1, 2, \dots$, define the cumulative marketwide stock return between day t and day $t + j$, by $\bar{\mathcal{R}}_{t,t+j}^I \equiv \prod_{k=1}^j \mathcal{R}_{t+k}^I$, the cumulative return of stock s between day t and day $t + j$, by $\bar{\mathcal{R}}_{t,t+j}^s \equiv \prod_{k=1}^j \mathcal{R}_{t+k}^s$, and the change in the 3-month Eurodollar future rate between day t and day $t + j$, with $\Delta i_{t,t+j} \equiv i_{t+j} - i_t$.

The first exercise we conduct consists of estimating the marketwide regression

$$\bar{\mathcal{R}}_{t-1,t-1+j}^I = a + b\Delta i_{t-1,t-1+j} + \epsilon_{t-1+j}, \quad (133)$$

for $t \in S_1$, with $j = 2$, where ϵ_{t-1+j} is an exogenous shock to the asset return. Notice (19) is a special case of (133) with $j = 1$. The second exercise consists of estimating

$$\bar{\mathcal{R}}_{t-1,t-1+j}^s = a + b\Delta i_{t-1,t-1+j} + \epsilon_{t-1+j} \quad (134)$$

with $j = 2$, for $t \in S_1$ and $s = 1, \dots, 20$, where s represents each of the twenty liquidity portfolios constructed in Section 5.3, and ϵ_{t-1+j} is an exogenous shock to the asset return. Since we want to estimate the effects of the day- t policy surprise on the cumulative return between the end of day $t-1$ and the end of day $t+1$, we instrument for $\Delta i_{t,t+j}$ using the daily *imputed change* in the 30-day federal funds futures rate from the level it has 20 minutes after the FOMC announcement

and the level it has 10 minutes before the FOMC announcement, i.e., the variable z_t as described in Appendix B (Section B.2). That is, we estimate b in (133) and in (134) using the following two-stage least squares (2SLS) procedure. Define $\Delta i_{t,t+j}^{ed} \equiv i_{t+j}^{ed} - i_t^{ed}$, where i_t^{ed} denotes the rate implied (for day t) by the 3-month Eurodollar futures contract with closest expiration date at or after day t . First, run the regression $\Delta i_{t-1,t-1+j}^{ed} = \kappa_0 + \kappa z_t + \eta_{t-1+j}$ on sample S_1 (where η_{t-1+j} is an error term) to obtain the OLS estimates of κ_0 and κ , namely $\hat{\kappa}_0$ and $\hat{\kappa}$. Second, construct the fitted values $\hat{z}_{t-1,t-1+j} \equiv \hat{\kappa}_0 + \hat{\kappa} z_t$ and run the regression (19) (or (134)) setting $\Delta i_{t-1,t-1+j} = \hat{z}_{t-1,t-1+j}$. The resulting marketwide and portfolio-by-portfolio estimates are reported in Table 5. All estimates are negative, and again, the magnitude of the response tends to be stronger for more liquid portfolios. For example, the two-day return of portfolio 20 responds 2.23 times more than the two-day return of portfolio 1, while (from Table 2) the announcement-day return of portfolio 20 responds 2.55 times more than the announcement-day return of portfolio 1. Thus, even much of the tilting in the announcement-day return responses to the policy shock is still noticeable when looking at two-day cumulated returns.

The third exercise we conduct consists of estimating the following regression of delayed individual stock returns (for the universe of stocks listed in the NYSE) on changes in the policy rate, an interaction term between the change in the policy rate and individual stock daily turnover rate, and several controls, i.e.,

$$\begin{aligned} \bar{\mathcal{R}}_{t-1,t-1+j}^s = & \beta_0 + \beta_1 \Delta i_{t-1,t-1+j} + \beta_2 \mathcal{T}_t^s + \beta_3 (\Delta i_{t-1,t-1+j} - \Delta i) \times \bar{\mathcal{T}}_t^s \\ & + D_s + D_t + \beta_4 (\Delta i_{t-1,t-1+j})^2 + \beta_5 (\mathcal{T}_t^s)^2 + \varepsilon_{t-1,t-1+j}^s, \end{aligned} \quad (135)$$

with $j = 2$, for all $t \in S_1$ and all individual stocks, s , where D_s is a stock fixed effect, D_t is a quarterly time dummy, and $\varepsilon_{t-1,t-1+j}^s$ is the error term corresponding to stock s on policy announcement day t , $\bar{\mathcal{T}}_t^s \equiv \mathcal{T}_t^s - \mathcal{T}$, and Δi and \mathcal{T} denote the sample averages of $\Delta i_{t-1,t-1+j}$ and \mathcal{T}_t^s , respectively. We estimate seven different specifications based on (135). These seven specifications correspond to specifications (I), (II), (III), (IV), (VI), (VII), and (VIII) in Section 5.3. In every specification, the measure of daily turnover of a stock s , namely \mathcal{T}_t^s , is measured as in the estimation of (20). In specification (I), $\Delta i_{t-1,t-1+j}$ is instrumented for with z_t , as explained above. In all other specifications, we proxy for $\Delta i_{t-1,t-1+j} \equiv v_{t-1,t-1+j}^1$ and $(\Delta i_{t-1,t-1+j} - \Delta i) \times \bar{\mathcal{T}}_t^s \equiv v_{t-1,t-1+j}^2$ as follows. We first run the following two regressions (i.e., for $i = 1, 2$)

$$v_{t-1,t-1+j}^i = \kappa_0^i + \kappa_1^i z_t + \kappa_2^i (z_t \times \mathcal{T}_t^s) + \eta_{t-1+j}^i \quad (136)$$

on sample S_1 (where η_{t-1+j}^i is an error term) to obtain the OLS estimates of $(\kappa_0^i, \kappa_1^i, \kappa_2^i)_{i=1,2}$, namely $(\hat{\kappa}_0^i, \hat{\kappa}_1^i, \hat{\kappa}_2^i)_{i=1,2}$. We then construct the fitted values $\hat{v}_{t-1,t-1+j}^i \equiv \kappa_0^i + \kappa_1^i z_t + \kappa_2^i (z_t \times \mathcal{T}_t^s)$ for $i = 1, 2$, and run the regression (135) setting $\Delta i_{t-1,t-1+j} = \hat{v}_{t-1,t-1+j}^1$ and $(\Delta i_{t-1,t-1+j} - \Delta i) \times \bar{\mathcal{T}}_t^s = \hat{v}_{t-1,t-1+j}^2$. Whenever $(\Delta i_{t-1,t-1+j})^2$ appears in a particular specification of (135), we also include z_t^2 as an additional regressor in the first-stage regressions (136).

The results are in Table 6. The estimate of interest, β_3 , is large, negative, and statistically significant in all specifications. This means that the magnitude of the negative effect of unexpected changes in the policy rate on two-day cumulated equity returns is still larger for stocks with higher turnover liquidity.

D.2 Disaggregative announcement-day effects with additional controls

In addition to the specifications (I)-(IX) of (20) discussed in Section 5.3, in this section we report the results of three more specifications, labeled (X), (XI), and (XII), that incorporate additional control variables. The general regression we fit is now

$$\begin{aligned}
\mathcal{R}_t^s &= \beta_0 + \beta_1 \Delta i_t + \beta_2 \mathcal{T}_t^s + \beta_3 \bar{\mathcal{T}}_t^s \times \bar{\Delta i}_t \\
&+ D_s + D_t + D_I + \beta_4 (\Delta i_t)^2 + \beta_5 (\mathcal{T}_t^s)^2 \\
&+ \beta_6 \beta_{1t}^s + \beta_7 \bar{\beta}_{1t}^s \times \bar{\Delta i}_t \\
&+ \beta_8 \beta_{2t}^s + \beta_9 \bar{\beta}_{2t}^s \times \bar{\Delta i}_t \\
&+ \beta_{10} \beta_{3t}^s + \beta_{11} \bar{\beta}_{3t}^s \times \bar{\Delta i}_t \\
&+ \beta_{12} L_t^s + \beta_{13} \bar{L}_t^s \times \bar{\Delta i}_t + \varepsilon_{st},
\end{aligned} \tag{137}$$

where D_I is a dummy for the Fama-French ten-industry classification, L_t^s is the measure of the bank leverage of company s at date t constructed by Ippolito et al. (2018), and β_{jt}^s is the “beta” corresponding to factor “ $f_{j,t}$ ” with $j \in \{1, 2, 3\}$ for announcement day t that we estimated from the multi-factor regression (82) (recall $f_{1,t} = MKT_t$, $f_{2,t} = HML_t$, and $f_{3,t} = SMB_t$; see Section B.3 for details).⁶⁴ All other variables are as defined in Section 5.3. Also as in Section 5.3, a “ $\bar{}$ ” on top of a variable denotes deviation from the sample average, i.e., $\bar{\beta}_{jt}^s \equiv (\beta_{jt}^s - \beta_j)$ and $\bar{L}_t^s \equiv (L_t^s - L)$, where β_j and L denote the sample averages of β_{jt}^s and L_t^s . The industry dummy D_I addresses the potential concern that the turnover rate of a stock may be correlated

⁶⁴In Section B.3 we used $\beta_j^s(k)$ to denote the estimate for the beta corresponding to factor j for stock s , estimated on the sample consisting of all trading days between the policy announcement days t_{k-1} and t_k . Since t_k is the date of the k^{th} announcement, we have $\beta_{jt_k}^s = \beta_j^s(k)$.

with the industry to which the stock belongs. Incorporating the announcement-date “betas” $\{\beta_{jt}^s\}_{j=1}^3$ addresses the potential concern that the differential return response to policy rate shocks for stocks with different turnover liquidity may be driven by heterogeneous exposure to other aggregate factors. Specifically the betas $\{\beta_{jt}^s\}_{j=1}^3$ control for the effects on stock returns of the three standard Fama-French factors—after controlling for the risk exposure to aggregate turnover of the stock market (as captured by β_0^s in (82)).⁶⁵ The additional control variable, bank leverage L_t^s , addresses the potential concern that the differential return responses that we attribute to the turnover rate of a stock may instead reflect some other fundamentals of a firm, such as its reliance on debt.

Specifications (I)-(IX) are as in Section 5.3. Specification (X) adds D_I to specification (IX). Specification (XI) adds $\{\beta_{jt}^s\}_{j=1}^3$ and the corresponding cross terms, $\{\overline{\beta_{jt}^s} \times \overline{\Delta i_t}\}_{j=1}^3$, to specification (X). Specification (XII) adds L_t^s and the cross term $\overline{L_t^s} \times \overline{\Delta i_t}$ to specification (XI). In every case, the coefficient of interest is β_3 .

The results for specifications (I)-(XI) for our baseline sample period (January 3, 1994 through December 31, 2007) are reported in Table 7. The results for specification (XII) reported in Table 8 are estimated for the sample period June 26, 2002 to December 31, 2007 since the company-specific leverage data from Ippolito et al. (2018) starts on June 26, 2002. For comparison purposes, in Table 8 we also report the results of specifications (IX), (X), and (XI) for the same sample period. The main conclusion is that in all specifications, the estimate of β_3 is negative, large in magnitude, and significant.

D.3 NASDAQ stocks

In this section we use daily time series for all individual stocks in the National Association of Securities Dealer Automated Quotation system (NASDAQ) from CRSP to estimate the aggregate and disaggregative return responses of Section 5.3 for the same sample period. We perform the same estimations as in Section 5.3. The estimates for marketwide return and turnover are reported in Table 9, which is analogous to Table 1. The estimates obtained from the portfolio-by-portfolio regressions are reported in Table 10, which is analogous to Table 2. The estimates from the nine specifications based on (20) are reported in Table 11, which is analogous to Table 3. The tilting in returns across liquidity portfolios in response to the

⁶⁵Because the Fama-French factors are reduced-form factors that may partly capture partly the effect of the turnover liquidity transmission mechanism, we control for the return exposure to the aggregate turnover rate in order to obtain the betas that are net of the influence of the turnover liquidity factor.

monetary policy shock is even stronger than for the NYSE stocks.

D.4 Value-weighted returns

Let \mathbb{P} denote a portfolio of stocks, i.e., a collection of stocks, each denoted by s , and let $N(\mathbb{P})$ denote the number of stocks in \mathbb{P} . In the portfolio-by-portfolio regressions of Section 5.3, we defined the average return of portfolio \mathbb{P} on day t as

$$\sum_{s \in \mathbb{P}} \frac{1}{N(\mathbb{P})} \mathcal{R}_t^s.$$

In this section we redo the same estimations using the value-weighted return, defined as

$$\sum_{s \in \mathbb{P}} \omega_t^s \mathcal{R}_t^s,$$

with

$$\omega_t^s \equiv \frac{P_{t-1}^s K_t^s}{\sum_{i \in \mathbb{P}} P_{t-1}^i K_t^i},$$

where K_t^s denotes the number of outstanding shares for stock s on day t . The results for the NYSE are summarized in Table 12. All the estimates are negative, as predicted by the theory. Also, the magnitude of the (statistically significant) estimates tends to increase with the turnover liquidity of the portfolio.

D.5 Results for the 2002-2007 subsample

The empirical finding that surprise increases in the nominal policy rate cause sizable reductions in real stock returns on announcement days of the FOMC is well established for sample periods ranging roughly from the early 1990's until 2002. For example, Bernanke and Kuttner (2005) use a sample that runs from June 1989 to December 2002, and Rigobon and Sack (2004) use a sample that runs from January 1994 to November 2001. We have found that both their empirical results for stocks, and our additional findings regarding the turnover-liquidity mechanism, hold for the longer sample that runs from January 1994 to December 2007. Table 13 reports the estimates for specifications (I)-(IX) of (20), for the sample period 2002-2007. The table shows that our empirical findings, and the results for stocks in Bernanke and Kuttner (2005) and Rigobon and Sack (2004) also hold for this more recent subsample.

D.6 Nominal-real interest rate passthrough

In the baseline calibration of Section 6 we set $w = .8$, which implies a 100 bp increase in the nominal rate is associated with a 80 bp increase in the real rate and a 20 bp increase in expected inflation. As a robustness check we have also set $w = 1$ and recalibrated the model to fit the same data targets as the baseline calibration, and found that the quantitative performance of the theory is very similar to the case with $w = .8$. Here we report results for the case with $w = 0$, which implies a 100 bp increase in the nominal rate is associated with a 100 bp increase in expected inflation and the real rate remains constant. Specifically, we consider an economy with $w = 0$, recalibrate the model to fit the same data targets as the baseline calibration, and carry out Exercise 1 as described in Section 6.3. The theory is able to generate most of the announcement-day tilting in cross-sectional returns. The results are shown in Figure 11.

Portfolio	Return	
	Estimate	Std dev
1	-4.20 ^{***}	1.21
2	-4.15 ^{***}	1.25
3	-4.61 ^{***}	1.29
4	-4.35 ^{***}	1.32
5	-4.87 ^{***}	1.41
6	-4.45 ^{***}	1.54
7	-5.25 ^{***}	1.43
8	-4.91 ^{***}	1.55
9	-4.65 ^{***}	1.65
10	-5.90 ^{***}	1.64
11	-6.07 ^{***}	1.47
12	-6.06 ^{***}	1.70
13	-6.80 ^{***}	1.59
14	-6.12 ^{***}	1.57
15	-7.79 ^{***}	1.66
16	-7.08 ^{***}	1.78
17	-8.91 ^{***}	2.07
18	-9.32 ^{***}	1.97
19	-8.90 ^{***}	2.19
20	-9.35 ^{***}	2.56
NYSE	-6.18 ^{***}	1.49

Table 5: Two-day responses of stock returns to monetary policy across liquidity portfolios (HFIV estimates). ^{***} denotes significance at 1% level, ^{**} significance at 5% level, ^{*} significance at 10% level.

Variable	(I)	(II)	(III)	(IV)	(VI)	(VII)	(VIII)
$\Delta i_{t-1,t+1}$	-6.13 (.141)	-6.25 (.144)	-6.29 (.142)	-6.10 (.161)	-5.59 (.158)	-5.59 (.157)	-5.90 (.187)
\mathcal{T}_t^s	3364 (207)	3593 (210)	2777 (274)	2124 (231)	6090 (441)	5020 (548)	5374 (464)
$\overline{\mathcal{T}}_t^s \times (\Delta i_{t-1,t+1} - \Delta i)$		-434.20 (39.68)	-429.91 (39.21)	-248.50 (39.14)	-423.18 (39.17)	-422.76 (38.82)	-232.91 (38.85)
D_s			yes			yes	
D_t				yes			yes
$(\Delta i_{t-1,t+1})^2$					.044 (.009)	.046 (.009)	.012 (.011)
$(\mathcal{T}_t^s)^2$					-103202 (20442)	-83014.5 (22947)	-131721 (20333)
R^2	.0157	.0152	.0140	.0645	.0202	.0191	.0669

Table 6: Effects of monetary policy on two-day stock returns of NYSE individual stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (20). Number of observations: 205,657. Standard errors in parenthesis. All estimates are significant at 1% level, except for $(\Delta i_{t-1,t+1})^2$ in regression (VIII).

Variable	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)	(XI)
Δi_t	-5.37 (.11)	-5.56 (.11)	-5.60 (.13)	-5.83 (.12)	-5.82 (.13)	-5.21 (.099)	-5.23 (.098)	-5.30 (.110)	-5.30 (.112)	-5.30 (.112)	-5.36 (.127)
$\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$		-553 (29)	-557 (30)	-492 (30)	-491 (32)	-554 (29)	-560 (31)	-485 (30)	-487 (32)	-485 (32)	-539 (34)
D_s			yes		yes		yes		yes	yes	yes
D_t				yes	yes			yes	yes	yes	yes
D_I										yes	yes
$(\Delta i_t)^2$						.04 (.008)	.04 (.008)	.05 (.009)	.05 (.010)	.05 (.010)	.06 (.010)
$(\mathcal{T}_t^s)^2$						-53852 (14751)	-57208 (15093)	-63775 (14887)	-56275 (15597)	-55883 (15650)	-67669 (16444)
$\overline{\beta_{1t}^s} \times \overline{\Delta i_t}$											.08 (.21)
$\overline{\beta_{2t}^s} \times \overline{\Delta i_t}$											.37 (.17)
$\overline{\beta_{3t}^s} \times \overline{\Delta i_t}$											.38 (.11)
R^2	.0241	.0286	.0286	.0778	.0778	.0290	.0290	.0783	.0784	.0781	.0933

Table 7: Effects of monetary policy on stock returns of individual NYSE stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (137). Number of observations: 205,760. Standard errors in parentheses. All estimates are significant at the 1 percent level except $\overline{\beta_{2t}^s} \times \overline{\Delta i_t}$, which is significant at the 5 percent level and $\overline{\beta_{1t}^s} \times \overline{\Delta i_t}$, which is insignificant.

Variable	(IX)	(X)	(XI)	(XII)
Δi_t	-8.98 (.315)	-8.98 (.316)	-9.40 (.350)	-9.38 (.347)
$\overline{T}_t^s \times \overline{\Delta i}_t$	-272 (40)	-273 (40)	-251 (41)	-253 (41)
D_s	yes	yes	yes	yes
D_t	yes	yes	yes	yes
D_I		yes	yes	yes
$\overline{\beta}_{1t}^s \times \overline{\Delta i}_t$			-4.69 (.38)	-4.71 (.38)
$\overline{\beta}_{2t}^s \times \overline{\Delta i}_t$			-1.48 (.20)	1.49 (.20)
$\overline{\beta}_{3t}^s \times \overline{\Delta i}_t$			.87 (.11)	.87 (.12)
$\overline{L}_t^s \times \overline{\Delta i}_t$				-2.30 (2.06)
R^2	.1528	.1502	.1913	.1913

Table 8: Effects of monetary policy on stock returns of individual NYSE stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (137), estimated for the sample period June 26, 2002 to December 31, 2007. Number of observations: 44,734. Standard errors in parentheses. All estimates are significant at the 1 percent level, except for $\overline{L}_t^s \times \overline{\Delta i}_t$, which is insignificant.

	E-based		H-based		HFIV	
	Estimate	Std. dev.	Estimate	Std. dev.	Estimate	Std. dev.
Return	-6.37 ^{***}	2.11	-11.12 ^{***}	3.74	-12.97 ^{***}	3.58
Turnover	-.00004 ^{***}	.00001	-.00006 ^{**}	.00003	-.00006 ^{***}	.00001

Table 9: Empirical response of NASDAQ marketwide stock returns to monetary policy. ^{***} denotes significance at the 1 percent level, ^{**} significance at the 5 percent level, ^{*} significance at the 10 percent level.

Portfolio	Turnover	E-based			H-based			HFIV		
		Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.
1	.08	-1.64**	.64	-1.76	1.19	-3.38***	1.18			
2	.14	-1.51**	.71	-3.05	1.60	-2.87**	1.42			
3	.21	-1.96***	.65	-4.87***	1.86	-4.49***	1.36			
4	.28	-2.25**	.98	-4.71**	1.91	-5.27***	1.54			
5	.36	-4.07***	1.01	-7.52***	2.55	-7.16***	1.79			
6	.44	-3.48***	1.24	-6.85***	2.57	-7.78***	2.19			
7	.54	-3.75***	1.37	-6.22***	2.40	-7.45***	2.71			
8	.64	-5.04***	1.42	-9.26***	3.26	-8.94***	2.55			
9	.76	-5.81***	1.80	-9.84***	3.46	-10.13***	3.31			
10	.89	-4.46**	1.73	-8.24**	3.34	-11.23***	3.23			
11	1.04	-6.28***	1.98	-11.58***	4.18	-12.21***	3.61			
12	1.21	-6.12***	1.79	-11.30***	4.13	-12.12***	3.50			
13	1.41	-6.69**	2.62	-10.56***	4.03	-13.85***	4.35			
14	1.61	-7.71***	2.45	-12.89***	4.47	-14.72***	4.19			
15	1.88	-8.92***	2.98	-15.20***	5.18	-18.29***	4.96			
16	2.22	-9.25***	3.06	-15.80***	5.38	-19.16***	5.11			
17	2.65	-9.14**	3.69	-15.22***	5.63	-20.11***	6.75			
18	3.26	-11.18***	4.05	-19.63***	6.73	-22.85***	6.36			
19	4.26	-12.23***	4.37	-21.40***	7.30	-24.80***	6.46			
20	6.65	-15.87***	6.04	-26.68***	9.43	-32.69***	8.33			
NASDAQ	1.53	-6.37***	2.11	-11.12***	3.74	-12.97***	3.58			

Table 10: Empirical responses of NASDAQ stock returns to monetary policy across liquidity portfolios (1994-2007 sample).
*** denotes significance at 1% level, ** significance at 5% level, * significance at 10% level.

Variable	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Δi_t	-6.32 (.129)	-6.56 (.128)	-6.63 (.128)	-6.37 (.139)	-6.38 (.139)	-3.88 (.121)	-3.91 (.121)	-3.50 (.139)	-3.50 (.139)
\mathcal{T}_t^s	1655 (95)	1655 (94)	1093 (124)	1451 (93)	892 (123)	3214 (196)	2853 (267)	2894 (194)	2414 (266)
$\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$		-643 (23)	-649 (22)	-632 (22)	-636 (22)	-640 (22)	-646 (22)	-625 (22)	-628 (21)
D_s			yes		yes		yes		yes
D_t				yes	yes			yes	yes
$(\Delta i_t)^2$						.263 (.009)	.268 (.009)	.285 (.011)	.286 (.011)
$(\mathcal{T}_t^s)^2$						-44321 (5776)	-43028 (6708)	-42754 (5725)	-39000 (6648)
R^2	.0096	.0145	.0144	.0317	.0316	.0179	.0179	.0342	.0340

Table 11: Effects of monetary policy on stock returns of individual NASDAQ stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (20). Number of observations: 482,825. Standard errors in parenthesis. All estimates are significant at 1% level.

Portfolio	Turnover	E-based			H-based			HFIV		
		Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.	Estimate	Std. dev.	Std. dev.
1	.17	-2.74**	1.14		-6.04**	2.96		-4.06*	2.26	
2	.32	-3.67***	.92		-10.21**	4.61		-6.25***	2.35	
3	.43	-5.06***	1.75		-9.13**	4.50		-8.32**	3.55	
4	.52	-2.93**	1.73		-10.75*	5.58		-1.48	3.08	
5	.59	-4.25***	2.07		-11.45**	5.20		-3.55	4.18	
6	.66	-5.64***	1.46		-11.82***	3.75		-7.21***	2.61	
7	.73	-4.51***	1.61		-9.83***	3.59		-5.10	3.39	
8	.80	-6.23***	1.59		-10.75**	4.39		-9.44***	3.53	
9	.87	-4.81***	1.50		-10.95**	5.49		-6.31**	2.90	
10	.94	-5.56***	1.29		-12.76**	5.01		-8.38***	2.81	
11	1.01	-8.30***	2.10		-13.00***	4.85		-13.06***	4.20	
12	1.11	-6.74***	1.97		-11.06**	4.67		-12.24***	4.74	
13	1.21	-8.57***	2.10		-13.93***	4.37		-14.38***	3.67	
14	1.32	-6.38***	1.66		-14.72***	5.16		-10.42***	3.12	
15	1.45	-9.78***	2.42		-16.24***	4.75		-16.21***	3.61	
16	1.60	-10.21***	3.20		-15.47***	5.04		-19.31***	6.05	
17	1.79	-10.06***	1.85		-19.65***	6.63		-16.28***	3.66	
18	2.07	-10.04***	2.50		-18.32***	6.16		-18.07***	4.79	
19	2.50	-12.00***	3.09		-22.33***	7.46		-21.38***	5.59	
20	3.57	-9.22***	2.84		-18.88***	6.86		-18.69***	5.03	

Table 12: Empirical responses of stock returns to monetary policy across NYSE value-weighted liquidity portfolios (1994-2007 sample). *** denotes significance at 1% level, ** significance at 5% level, * significance at 10% level.

Variable	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Δi_t	-8.49 (.19)	-8.21 (.19)	-8.30 (.18)	-8.20 (.22)	-8.15 (.21)	-9.47 (.19)	-9.55 (.19)	-9.11 (.25)	-9.06 (.22)
\mathcal{T}_t^s	2390 (194)	2356 (194)	2879 (253)	480 (192)	377 (273)	3550 (440)	4867 (564)	1882 (440)	1037 (595)
$\overline{\mathcal{T}}_t^s \times \overline{\Delta i_t}$		-436 (39)	-430 (32)	-297 (38)	-305 (32)	-395 (38)	-391 (31)	-280 (38)	-288 (32)
D_s			yes		yes		yes		yes
D_t				yes	yes			yes	yes
$(\Delta i_t)^2$						.57 (.017)	.56 (.016)	.40 (.025)	.39 (.022)
$(\mathcal{T}_t^s)^2$						-47089 (17542)	-68872 (18930)	-43233 (17503)	-33071 (19449)
R^2	.0343	.0376	.0374	.1387	.1385	.0506	.0502	.1431	.1429

Table 13: Effects of monetary policy on stock returns of individual NYSE stocks (both in basis points). Each column reports the coefficients from a separate pooled OLS regression based on (20) for the sample period 2002-2007. Number of observations: 78,942. Standard errors in parentheses. All estimates are significant at the 1 percent level.

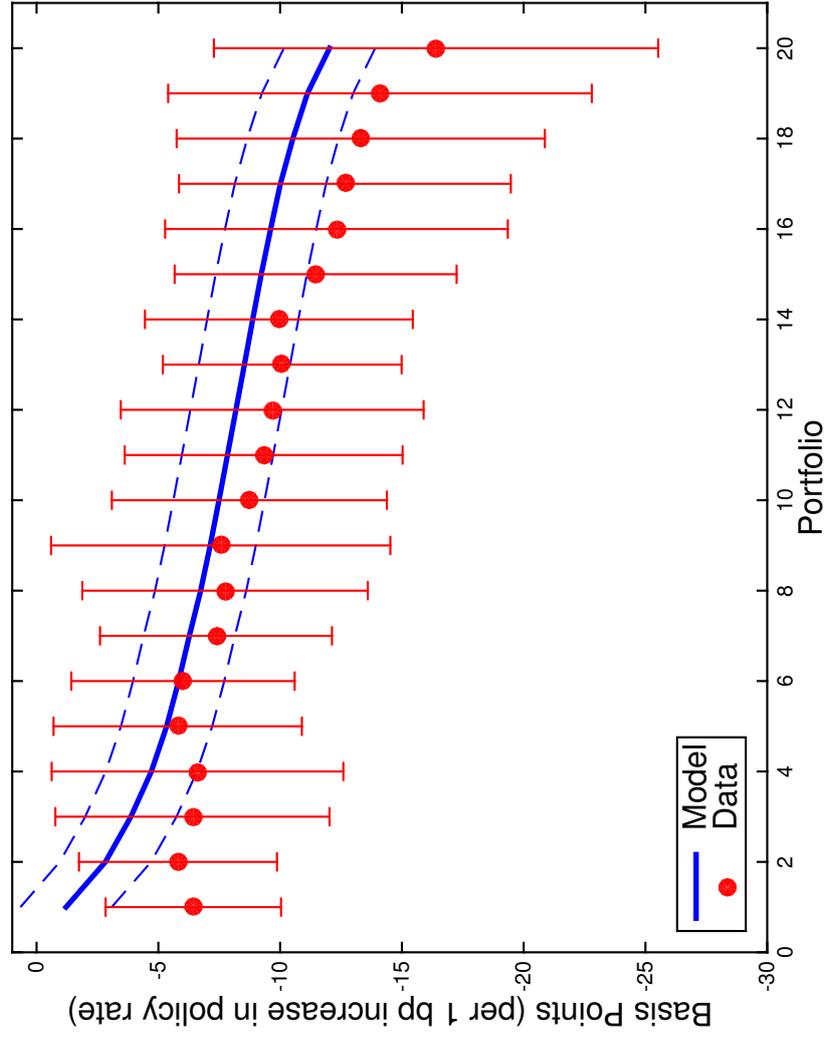


Figure 11: Cross-sectional announcement-day responses of stock returns to policy rate for the model with $w = 0$.

E Supplementary material: Literature

The empirical component of our paper (Section 5) is related to a large empirical literature that studies the effect of monetary policy shocks on asset prices. Like many of these studies, we identify monetary policy shocks by focusing on the reaction of asset prices in a narrow time window around FOMC monetary policy announcements. Cook and Hahn (1989), for example, use this kind of event-study identification strategy (with an event window of one day) to estimate the effects of changes in the federal funds rate on bond rates. Kuttner (2001) conducts a similar analysis but shows the importance of focusing on unexpected policy changes, which he proxies for with federal funds futures data. Cochrane and Piazzesi (2002) estimate the effect of monetary policy announcements on the yield curve using a one-day window around the FOMC announcement and the daily change in the one-month Eurodollar rate to proxy for unexpected changes in the federal funds rate target. Bernanke and Kuttner (2005) use daily event windows around FOMC announcements to estimate the effect of unexpected changes in the federal funds rate (measured using federal funds futures data) on the return of broad stock indices. Gürkaynak, Sack and Swanson (2005) focus on intraday event windows around FOMC announcements (30 minutes or 60 minutes wide) to estimate the effects on the S&P500 return and several Treasury yields of unexpected changes in the federal funds target and “forward guidance” (i.e., information on the future path of policy contained in the announcement). More recently, Hanson and Stein (2015) estimate the effect of monetary policy shocks on the nominal and real Treasury yield curves using a two-day window around the announcement. Nakamura and Steinsson (2015) also estimate the effects of monetary policy shocks on the nominal and real Treasury yield curves, but they use a 30-minute window around the announcement. Gertler and Karadi (2015) also use a 30-minute window around the announcement to estimate the response of bond yields and credit spreads to monetary policy shocks. Rigobon and Sack (2004) propose a heteroskedasticity-based estimator to correct for possible simultaneity biases remaining in these event-study regressions.

Relatively fewer papers have attempted to identify the precise mechanism through which surprise increases in the federal funds rate lead to a reduction in stock prices. Bernanke and Kuttner (2005), for example, take one step in this direction by analyzing the response of more disaggregated indices, in particular 10 industry-based portfolios. They find that the precision of their estimates is not sufficient to reject the hypothesis of an equal reaction for all 10 industries.

Firms differ along many dimensions, however, and a number of studies have focused on how these may be related to different responses of their stock prices to policy shocks. Ehrmann and Fratzscher (2004), for example, find that firms with low cash flows, small firms, firms with low credit ratings, firms with high price-earnings multiples, or firms with high Tobin's q exhibit a higher sensitivity to monetary policy shocks. Ippolito et al. (2013, 2018) find that the stock prices of bank-dependent firms that borrow from financially weaker banks display a stronger sensitivity to monetary policy shocks, while bank-dependent firms that hedge against interest rate risk display a lower sensitivity to monetary policy shocks. Gorodnichenko and Weber (2016) document that after monetary policy announcements, the conditional volatility of stock market returns rises more for firms with stickier prices than for firms with more flexible prices. Relative to this literature, our contribution is to document and offer a theory of the *turnover-liquidity transmission mechanism* that channels monetary policy to asset prices.

From a theoretical standpoint, the model we develop in this paper bridges the search-theoretic monetary literature that has largely focused on macro issues and the search-theoretic financial OTC literature that focuses on microstructure considerations. Specifically, we embed an OTC financial trading arrangement similar to Duffie et al. (2005) into a Lagos and Wright (2005) economy. Despite several common ingredients with those papers, our formulation is different from previous work along two important dimensions.

In the standard formulations of the Lagos-Wright framework, money (and sometimes other assets) are used as payment instruments to purchase consumption goods in bilateral markets mediated by search. We instead posit that money is used as a medium of exchange in OTC markets for financial assets. In the standard monetary model, money and other liquid assets help to allocate goods from producers to consumers, while in our current formulation, money helps to allocate financial assets among traders with heterogeneous valuations. This shift in the nature of the gains from trade offers a different perspective that delivers novel insights into the interaction between monetary policy and financial markets. For example, from a normative standpoint, the new perspective emphasizes a new angle on the welfare cost of inflation that is associated with the distortion of the optimal allocation of financial assets across investors with high and low valuations when real balances are scarce. From a positive perspective, it explains the positive correlation between nominal bond yields and real equity yields, something that the conventional formulation in which monetary or real assets are used to buy consumption goods cannot do.

As a model of financial trade, an appealing feature of Duffie et al. (2005) is its realistic OTC market structure consisting of an interdealer market and bilateral negotiated trades between investors and between investors and dealers. In Duffie et al. (2005), agents who wish to buy assets pay sellers with linear-utility transfers. In addition, utility transfers from buyers to sellers are unconstrained, so effectively there is no bound on what buyers can afford to purchase in financial transactions. Our formulation keeps the appealing market structure of Duffie et al. (2005) but improves on its stylized model of financial transactions by considering traders who face standard budget constraints and use fiat money to purchase assets. These modifications make the standard OTC formulation amenable to general equilibrium analysis and deliver a natural transmission mechanism through which monetary policy influences asset prices and the standard measures of financial liquidity that are the main focus of the microstructure strand of the OTC literature.

Our theoretical work is related to several previous studies, e.g., Geromichalos et al. (2007), Jacquet and Tan (2012), Lagos and Rocheteau (2008), Lagos (2010a, 2010b, 2011), Lester et al. (2012), and Nosal and Rocheteau (2013), which introduce a real asset that can (at least to some degree) be used along with money as a medium of exchange for consumption goods in variants of Lagos and Wright (2005). These papers identify the liquidity value of the asset with its usefulness in exchange and find that when the asset is valuable as a medium of exchange, this manifests itself as a “liquidity premium” that makes the real asset price higher than the expected present discounted value of its financial dividend. High anticipated inflation reduces real money balances; this tightens bilateral trading constraints, which in turn increases the liquidity value and the real price of the asset. In contrast, we find that real asset prices are decreasing in the rate of anticipated inflation. There are some models that also build on Lagos and Wright (2005) where agents can use a real asset as collateral to borrow money that they subsequently use to purchase consumption goods. In those models, anticipated inflation reduces the demand for real balances, which in turn can reduce the real price of the collateral asset needed to borrow money (see, e.g., He et al., 2012, and Li and Li, 2012). The difference is that in our setup, inflation reduces the real asset price by constraining the reallocation of the financial asset from investors with low valuations to investors with relatively high valuations.⁶⁶

⁶⁶In the model that we have developed here, money is the only asset used as means of payment. It would be straightforward, however, to enrich the asset structure so that investors may choose to carry other real assets that can be used as means of payment in the OTC market, e.g., along the lines of Lagos and Rocheteau (2008) or Lagos (2010a, 2010b, 2011). As long as money is valued in equilibrium, we anticipate that the main results

We share with two recent papers, Geromichalos and Herrenbrueck (2016) and Trejos and Wright (2016), the general interest in bringing models of OTC trade in financial markets within the realm of modern monetary general equilibrium theory. Trejos and Wright (2016) offer an in-depth analysis of a model that nests Duffie et al. (2005) and the prototypical “second generation” monetary search model with divisible goods, indivisible money, and a unit upper bound on individual money holdings (e.g., Shi, 1995 or Trejos and Wright, 1995). Trejos and Wright (2016) emphasize the different nature of the gains from trade in both classes of models. In monetary models, agents value consumption goods differently and use assets to buy goods, while in Duffie et al. (2005), agents trade because they value assets differently, and goods that are valued the same by all investors are used to pay for asset purchases. In our formulation, there are gains from trading assets, as in Duffie et al. (2005), but agents pay with money, as in standard monetary models. Another difference with Trejos and Wright (2016) is that rather than assuming indivisible assets and a unit upper bound on individual asset holdings, as in Shi (1995), Trejos and Wright (1995), and Duffie et al. (2005), we work with divisible assets and unrestricted portfolios, as in Lagos and Wright (2005) and Lagos and Rocheteau (2009).

Geromichalos and Herrenbrueck (2016) extend Lagos and Wright (2005) by incorporating a real asset that by assumption cannot be used to purchase goods in the decentralized market (as usual, at the end of every period agents choose next-period money and asset portfolios in a centralized market). The twist is that at the very beginning of every period, agents learn whether they will want to buy or sell consumption goods in the subsequent decentralized market, and at that point they have access to a bilateral search market where they can retrade money and assets. This market allows agents to rebalance their positions depending on their need for money, e.g., those who will be buyers seek to buy money and sell assets. So although assets cannot be directly used to purchase consumption goods as in Geromichalos et al. (2007) or Lagos and Rocheteau (2008), agents can use assets to buy goods indirectly, i.e., by exchanging them for cash in the additional bilateral trading round at the beginning of the period. Geromichalos and Herrenbrueck use the model to revisit the link between asset prices and inflation. Mattesini and Nosal (2016) study a related model that combines elements of Geromichalos and Herrenbrueck (2016) and elements of Lagos and Zhang (2015) but considers a new market structure for the interdealer market.

The fact that the equilibrium asset price is larger than the expected present discounted value

emphasized here would continue to hold.

that any agent assigns to the dividend stream is reminiscent of the literature on speculative trading that can be traced back to Harrison and Kreps (1978). As in Harrison and Kreps and more recent work, e.g., Scheinkman and Xiong (2003a, 2003b) and Scheinkman (2013), speculation in our model arises because traders have heterogeneous asset valuations that change over time: investors are willing to pay for the asset more than the present discounted value that they assign to the dividend stream, in anticipation of the capital gain they expect to obtain when reselling the asset to higher-valuation investors in the future. In terms of differences, in the work of Harrison and Kreps or Scheinkman and Xiong, traders have heterogeneous stubborn beliefs about the stochastic dividend process, and their motive for trading is that they all believe (at least some of them mistakenly) that by trading the asset they can profit at the expense of others. In our formulation, traders simply have stochastic heterogeneous valuations for the dividend, as in Duffie et al. (2005). Our model offers a new angle on the speculative premium embedded in the asset price, by showing how it depends on the underlying financial market structure and the prevailing monetary policy that jointly determine the likelihood and profitability of future resale opportunities. Through this mechanism, our theory can generate a positive correlation between trade volume and the size of speculative premia, a key stylized fact that the theory of Scheinkman and Xiong (2003b) also explains. In Lagos and Zhang (2015) we use a model similar to the one developed in this paper to explain the correlation between the real yield on stocks and the nominal yield on Treasury bonds at low frequencies—a well known puzzling empirical observation often referred to as the “Fed Model.” In that paper we also show the model can exhibit rational expectations dynamic sunspot equilibria with recurring belief driven events that resemble liquidity crises, i.e., times of sharp persistent declines in asset prices, trade volume, and dealer participation in market-making activity, accompanied by large increases in spreads and abnormally long trading delays. Asriyan et al. (2017) also study dynamic sunspot equilibria in an environment where the value of the asset is determined by a resale value option as in Harrison and Kreps (1978), but their key mechanism emphasizes information frictions (adverse selection) rather than OTC-style search frictions.

Piazzesi and Schneider (2016) also emphasize the general idea that the cost of liquidity can affect asset prices. In their model, the cost of liquidity to end users depends on the cost of leverage to intermediaries, while our model and our empirical work instead center on the role of the nominal policy rate, which represents the cost of holding the nominal assets used routinely to settle financial transactions (e.g., bank reserves, real money balances).