Turnover Liquidity and the Transmission of Monetary Policy

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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. Specifically, we make three contributions. First, we provide 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 and turnover 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 a number of 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. Section 3 describes the efficient allocation. Equilibrium is characterized in Section 4. Section 5 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 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 (or speculative "bubble") 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 6 is purely empirical. In it we confirm the finding, documented in previous empirical work, that surprise increases in the nominal policy rate cause sizable reductions in real stock returns on FOMC announcement days. A 1 basis point unexpected increase in the policy rate causes a decrease of between 4 and 8 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 95$^{\text{th}}$ percentile of turnover rates is about twelve times larger than that of a stock in the 5$^{\text{th}}$ percentile. The empirical evidence in this section suggests a mechanism whereby monetary policy affects asset prices through a reduction in turnover liquidity. In Section 7 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 8 concludes. Appendix A contains all proofs. Appendices B, C, and D, contain supplementary material. Appendix B deals with technical aspects of the data, estimation, and simulation. Appendix C contains additional theoretical derivations and results. 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 D places our contribution in the context of all these literatures.

2 Model

Time is represented by a sequence of periods indexed by $t = 0, 1, \ldots$. Each time 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 same factor, $\beta \in (0, 1)$. 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., $\Pr(\gamma_t \le \gamma) = \Gamma(\gamma)$, 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 $t \ge 1$, 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 an intermediation 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.

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

[1] As 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.

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

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

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 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 $[\varepsilon_L, \varepsilon_H]$.

[2]This 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).

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,

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

to maximize

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

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

$$\tilde{a}_{Dt} + \tilde{a}_{It} \leq A^s \tag{1}$$

$$a'_{Dt} + \alpha \int_{\varepsilon_L}^{\varepsilon_H} a'_{It} \left(d\varepsilon \right) \leq a_{Dt} + \alpha a_{It} \tag{2}$$

$$c_{Dt} + c_{It} \leq h_{Dt} + h_{It} \tag{3}$$

$$a_{Dt} = \delta \tilde{a}_{Dt} \tag{4}$$

$$a_{It} = \delta \tilde{a}_{It} + (1-\delta) A^s. \tag{5}$$

Proposition 1 *The efficient allocation satisfies the following two conditions for every t: (a) $\tilde{a}_{Dt} = A^s - \tilde{a}_{It} = A^s$ and (b) $a'_{It}(E) = \mathbb{I}_{\{\varepsilon_H \in E\}} \left[\delta + \alpha (1-\delta) \right] A^s / \alpha$, 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 $E \in \mathcal{F}([\varepsilon_L, \varepsilon_H])$.*

According to Proposition 1, 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.

4 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 $\boldsymbol{a}_{dt}$ and an investor with portfolio $\boldsymbol{a}_{it}$ and valuation ε. Let $\overline{\boldsymbol{a}}_t = (\overline{a}_t^m, \overline{a}_t^s)$ denote the investor's post-trade portfolio and let k_t denote the intermediation fee the dealer charges for his intermediation services. We assume the fee is expressed in terms of the general good and paid by the investor in the second subperiod.[3] We assume $(\overline{\boldsymbol{a}}_t, k_t)$ is determined by the Nash bargaining solution where the investor has bargaining power $\theta \in [0,1]$. Let $\hat{W}_t^D(\boldsymbol{a}_{dt}, k_t)$ denote the maximum expected discounted payoff of a dealer with portfolio $\boldsymbol{a}_{dt}$ and earned fee k_t when he reallocates his portfolio in the interdealer market of period t. Let $W_t^I(\boldsymbol{a}_{it}, -k_t)$ 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 $\boldsymbol{a}_{it}$ and has to pay a fee k_t. For each t, define a pair of functions $\overline{a}_t^k : \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H] \to \mathbb{R}_+$ for $k = m, s$ and a function $k_t : \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H] \to \mathbb{R}$, and let $\overline{\boldsymbol{a}}_t(\boldsymbol{a}_{it}, \varepsilon) = (\overline{a}_t^m(\boldsymbol{a}_{it}, \varepsilon), \overline{a}_t^s(\boldsymbol{a}_{it}, \varepsilon))$ for each $(\boldsymbol{a}_{it}, \varepsilon) \in \mathbb{R}_+^2 \times [\varepsilon_L, \varepsilon_H]$. We use $[\overline{\boldsymbol{a}}_t(\boldsymbol{a}_{it}, \varepsilon), k_t(\boldsymbol{a}_{it}, \varepsilon)]$ to represent the bargaining outcome for a bilateral meeting at time t between an investor with portfolio $\boldsymbol{a}_{it}$ and valuation ε, and a dealer with portfolio $\boldsymbol{a}_{dt}$. That is, $[\overline{\boldsymbol{a}}_t(\boldsymbol{a}_{it}, \varepsilon), k_t(\boldsymbol{a}_{it}, \varepsilon)]$ solves

$$\max_{(\overline{\boldsymbol{a}}_t, k_t) \in \mathbb{R}_+^2 \times \mathbb{R}} \left[\varepsilon y_t \overline{a}_t^s + W_t^I(\overline{\boldsymbol{a}}_t, -k_t) - \varepsilon y_t a_{it}^s - W_t^I(\boldsymbol{a}_{it}, 0)\right]^{\theta} [\hat{W}_t^D(\boldsymbol{a}_{dt}, k_t) - \hat{W}_t^D(\boldsymbol{a}_{dt}, 0)]^{1-\theta} \tag{6}$$
$$\text{s.t. } \overline{a}_t^m + p_t \overline{a}_t^s \leq a_{it}^m + p_t a_{it}^s$$
$$\hat{W}_t^D(\boldsymbol{a}_{dt}, 0) \leq \hat{W}_t^D(\boldsymbol{a}_{dt}, k_t)$$
$$\varepsilon y_t a_{it}^s + W_t^I(\boldsymbol{a}_{it}, 0) \leq \varepsilon y_t \overline{a}_t^s + W_t^I(\overline{\boldsymbol{a}}_t, -k_t),$$

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

Let $W_t^D(\boldsymbol{a}_t, k_t)$ 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 $\boldsymbol{a}_t$. Then the dealer's value of trading in the interdealer market is

$$\hat{W}_t^D(\boldsymbol{a}_t, k_t) = \max_{\hat{\boldsymbol{a}}_t \in \mathbb{R}_+^2} W_t^D(\hat{\boldsymbol{a}}_t, k_t) \tag{7}$$
$$\text{s.t. } \hat{a}_t^m + p_t \hat{a}_t^s \leq a_t^m + p_t a_t^s,$$

where $\hat{\boldsymbol{a}}_t \equiv (\hat{a}_t^m, \hat{a}_t^s)$. For each t, define a pair of functions, $\hat{a}_t^k : \mathbb{R}_+^2 \to \mathbb{R}_+$ for $k = m, s$, and let $\hat{\boldsymbol{a}}_t(\boldsymbol{a}_t) = (\hat{a}_t^m(\boldsymbol{a}_t), \hat{a}_t^s(\boldsymbol{a}_t))$ denote the solution to (7).

Let $V_t^D(\boldsymbol{a}_t)$ denote the maximum expected discounted payoff of a dealer who enters the OTC round of period t with portfolio $\boldsymbol{a}_t \equiv (a_t^m, a_t^s)$. Let $\boldsymbol{\phi}_t \equiv (\phi_t^m, \phi_t^s)$, where ϕ_t^m is the real

[3] In 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.

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,

$$W_t^D(\boldsymbol{a}_t, k_t) = \max_{(c_t, h_t, \tilde{\boldsymbol{a}}_{t+1}) \in \mathbb{R}_+^4} \left[c_t - h_t + \beta \mathbb{E}_t V_{t+1}^D(\boldsymbol{a}_{t+1})\right] \tag{8}$$
$$\text{s.t. } c_t + \boldsymbol{\phi}_t \tilde{\boldsymbol{a}}_{t+1} \leq h_t + k_t + \boldsymbol{\phi}_t \boldsymbol{a}_t,$$

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

$$W_t^I(\boldsymbol{a}_t, -k_t) = \max_{(c_t, h_t, \tilde{\boldsymbol{a}}_{t+1}) \in \mathbb{R}_+^4} \left[c_t - h_t + \beta \mathbb{E}_t \int V_{t+1}^I\left(\boldsymbol{a}_{t+1}, \varepsilon'\right) dG(\varepsilon')\right] \tag{9}$$
$$\text{s.t. } c_t + \boldsymbol{\phi}_t \tilde{\boldsymbol{a}}_{t+1} \leq h_t - k_t + \boldsymbol{\phi}_t \boldsymbol{a}_t + T_t,$$

where $\boldsymbol{a}_{t+1} = (\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s + (1-\delta) A^s)$ 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 $\boldsymbol{a}_t$ and valuation ε is

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

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

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

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, $A_{jt}^m = \int a_t^m dF_{jt}(\boldsymbol{a}_t)$ and $A_{jt}^s = \int a_t^s dF_{jt}(\boldsymbol{a}_t)$, where F_{jt} is the cumulative distribution function over portfolios $\boldsymbol{a}_t = (a_t^m, a_t^s)$ 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 $A^s_{It+1} = \delta \tilde{A}^s_{It+1} + (1-\delta) A^s$. Let $\bar{A}^m_{Dt}$ and $\bar{A}^s_{Dt}$ denote the quantities of money and shares held after the OTC round of trade of period t by all the dealers, and let $\bar{A}^m_{It}$ and $\bar{A}^s_{It}$ 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 $k \in \{s, m\}$, $\bar{A}^k_{Dt} = \int \hat{a}^k_t (\boldsymbol{a}_t)\, dF_{Dt} (\boldsymbol{a}_t)$ and $\bar{A}^k_{It} = \alpha \int \overline{a}^k_t(\boldsymbol{a}_t, \varepsilon) dH_{It}(\boldsymbol{a}_t, \varepsilon)$. We are now ready to define an equilibrium.

Definition 1 *An equilibrium is a sequence of prices, $\{1/p_t, \phi^m_t, \phi^s_t\}^\infty_{t=0}$, bilateral terms of trade in the OTC market, $\{\bar{\boldsymbol{a}}_t, k_t\}^\infty_{t=0}$, dealer portfolios, $\{\langle \hat{\boldsymbol{a}}_{dt}, \tilde{\boldsymbol{a}}_{dt+1}, \boldsymbol{a}_{dt+1}\rangle_{d\in\mathcal{D}}\}^\infty_{t=0}$, and investor portfolios, $\{\langle \tilde{\boldsymbol{a}}_{it+1}, \boldsymbol{a}_{it+1}\rangle_{i\in\mathcal{I}}\}^\infty_{t=0}$, such that for all t: (i) the bilateral terms of trade $\{\bar{\boldsymbol{a}}_t, k_t\}^\infty_{t=0}$ solve (6), (ii) taking prices and the bargaining protocol as given, the portfolios $\langle \hat{\boldsymbol{a}}_{dt}, \tilde{\boldsymbol{a}}_{dt+1}, \boldsymbol{a}_{dt+1}\rangle$ solve the individual dealer's optimization problems (7) and (8), and the portfolios $\langle \tilde{\boldsymbol{a}}_{it+1}, \boldsymbol{a}_{it+1}\rangle$ solve the individual investor's optimization problem (9), and (iii) prices, $\{1/p_t, \phi^m_t, \phi^s_t\}^\infty_{t=0}$, are such that all Walrasian markets clear, i.e., $\tilde{A}^s_{Dt+1} + \tilde{A}^s_{It+1} = A^s$ (the end-of-period t Walrasian market for equity clears), $\tilde{A}^m_{Dt+1} + \tilde{A}^m_{It+1} = A^m_{t+1}$ (the end-of-period t Walrasian market for money clears), and $\bar{A}^k_{Dt} + \bar{A}^k_{It} = A^k_{Dt} + \alpha A^k_{It}$ for $k = s, m$ (the period t OTC interdealer markets for equity and money clear). An equilibrium is "monetary" if $\phi^m_t > 0$ 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 $\varepsilon^*_t \equiv \frac{p_t \phi^m_t - \phi^s_t}{y_t}$ 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 $\boldsymbol{a}_t$ and valuation ε. The investor's post-trade portfolio, $[\overline{a}^m_t(\boldsymbol{a}_t, \varepsilon), \overline{a}^s_t(\boldsymbol{a}_t, \varepsilon)]$, is given by

$$\overline{a}^m_t(\boldsymbol{a}_t, \varepsilon) = [1 - \chi(\varepsilon^*_t, \varepsilon)] (a^m_t + p_t a^s_t)$$
$$\overline{a}^s_t(\boldsymbol{a}_t, \varepsilon) = \chi(\varepsilon^*_t, \varepsilon) (1/p_t) (a^m_t + p_t a^s_t),$$

and the intermediation fee charged by the dealer is

$$k_t(\boldsymbol{a}_t, \varepsilon) = (1-\theta)(\varepsilon - \varepsilon^*_t) \left[\chi(\varepsilon^*_t, \varepsilon) \frac{1}{p_t} a^m_t - [1 - \chi(\varepsilon^*_t, \varepsilon)] a^s_t \right] y_t.$$

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

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 stationary 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 stationary 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 $\mu \to \bar{\beta}$).

For the analysis that follows, it is convenient to define

$$\hat{\mu} \equiv \bar{\beta}\left[1 + \frac{(1-\alpha\theta)\left(1-\bar{\beta}\delta\right)(\hat{\varepsilon}-\bar{\varepsilon})}{\hat{\varepsilon}}\right] \quad \text{and} \quad \bar{\mu} \equiv \bar{\beta}\left[1 + \frac{\alpha\theta\left(1-\bar{\beta}\delta\right)(\bar{\varepsilon}-\varepsilon_L)}{\bar{\beta}\delta\bar{\varepsilon} + \left(1-\bar{\beta}\delta\right)\varepsilon_L}\right], \tag{10}$$

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

$$\bar{\varepsilon} - \hat{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\hat{\varepsilon}} (\hat{\varepsilon} - \varepsilon)\, dG(\varepsilon) = 0. \tag{11}$$

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

Proposition 2 *(i) A nonmonetary equilibrium exists for any parametrization. (ii) There is no stationary 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*

$$\phi_t^s = \phi^s y_t, \text{ with } \phi^s = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\bar{\varepsilon}. \tag{12}$$

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

$$\phi_t^s = \phi^s y_t, \text{ with } \phi^s = \begin{cases} \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\varepsilon^* & \text{if } \bar{\beta} < \mu \leq \hat{\mu} \\ \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon)\, dG(\varepsilon)\right] & \text{if } \hat{\mu} < \mu < \bar{\mu} \end{cases} \tag{13}$$

$$\bar{\phi}_t^s = \bar{\phi}^s y_t, \text{ with } \bar{\phi}^s = \varepsilon^* + \phi^s \tag{14}$$

$$\phi_t^m = Z \frac{y_t}{A_t^m} \tag{15}$$

$$p_t = \frac{\bar{\phi}^s}{Z} A_t^m, \tag{16}$$

where

$$Z = \frac{\alpha G(\varepsilon^*) A_I^s + A_D^s}{\alpha [1 - G(\varepsilon^*)]} (\varepsilon^* + \phi^s) \tag{17}$$

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

$$\frac{(1 - \bar{\beta}\delta) \int_{\varepsilon^*}^{\varepsilon_H} (\varepsilon - \varepsilon^*)\, dG(\varepsilon)}{\varepsilon^* + \bar{\beta}\delta \left[\bar{\varepsilon} - \varepsilon^* + \alpha\theta \int_{\varepsilon_L}^{\varepsilon^*} (\varepsilon^* - \varepsilon)\, dG(\varepsilon)\right] \mathbb{I}_{\{\hat{\mu} < \mu\}}} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} = 0. \tag{18}$$

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

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 stationary 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 (18) in part *(iv)* of Proposition 2. 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 2, $0 \leq \varepsilon_L < \varepsilon_t^*$ 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 $A_{It}^m = A_t^m$. 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, $\tilde{A}_{Dt+1}^s = A^s$ and $\tilde{A}_{It+1}^s = 0$ 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., $\tilde{A}_{Dt+1}^s = 0$ and $\tilde{A}_{It+1}^s = A^s$, so strictly speaking, in this case dealers only provide brokerage services in the OTC market. The intuition for this result is as follows.[4] 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 $\mu \to \bar{\mu}$ we

[4]See Lagos and Zhang (2015) for a more detailed discussion.

have $\varepsilon_t^* \to \varepsilon_L$, 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 2 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 (13). The cum dividend dollar price of equity in the OTC market, p_t, is given by (16). The real price of money (in terms of the second subperiod consumption good), ϕ_t^m, is given by (15). 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 (14).

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

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

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 $k = 0, 1, 2, ..., N$ (so k is the number of periods until the bond matures). Imagine the bond is illiquid in the sense that it cannot be traded in the OTC market. Then in a stationary monetary equilibrium, $q_{t,k}^B = (\bar{\beta}/\mu)^k$, and

$$\iota = \frac{\mu}{\bar{\beta}} - 1 \tag{19}$$

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 2 in which the money supply grows at rate $\bar{\beta}$ can be interpreted as a policy that implements the *Friedman rule*, i.e., $\iota = 0$ for all contingencies at all dates.

5 Implications

In this section, we discuss the main implications of the theory. Specifically, we show how asset prices and conventional measures of financial liquidity (spreads, trade volume, and dealer supply of immediacy) are determined by the quantity of money (the inflation regime) 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). We also show that generically, asset prices in the monetary economy exhibit a speculative premium (or speculative "bubble") whose size varies systematically with the inflation regime and the market microstructure.

5.1 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 the various traders.[5]

5.1.1 Inflation

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. As the nominal rate ι (or equivalently, the inflation rate μ) increases, equilibrium real money balances decline and the marginal investor valuation, ε^*, decreases, reflecting the fact that under the higher nominal rate, the investor valuation that was marginal under the lower nominal rate is no longer indifferent between carrying cash and equity out of the OTC market (he prefers equity). Since the marginal investor who prices the 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 nominal interest rate. All this is formalized in Proposition 3. The top row of Figure 1 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.

[5] In Appendix A (Proposition 8) we also establish the effect of a mean-preserving spread in the distribution of valuations on the equity price.

Proposition 3 *In the stationary monetary equilibrium: (i)* $\partial\phi^s/\partial\mu < 0$ *and* $\partial\phi^s/\partial\iota < 0$*, (ii)* $\partial\bar{\phi}^s/\partial\mu < 0$*, (iii)* $\partial Z/\partial\mu < 0$ *and* $\partial\phi_t^m/\partial\mu < 0$*.*

5.1.2 OTC frictions: trading delays and market power

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.[6] 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.[7] Proposition 4 formalizes these ideas. The bottom row of Figure 1 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.

Proposition 4 *In the stationary 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* $\mu \in (\hat{\mu}, \bar{\mu})$*.*

5.2 Financial liquidity

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

5.2.1 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 5 *In the stationary 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* $\alpha\theta$*.*

[6] This 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).

[7] Real balances can actually fall with α for $\mu \in (\bar{\beta}, \hat{\mu})$.

Part (i) of Proposition 5 is related to the discussion that followed Proposition 2. 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 5 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.

5.2.2 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 stationary 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 equivalently[8]

$$\mathcal{V} = 2\alpha G(\varepsilon^*) A_I^s + A_D^s. \tag{20}$$

[8]To obtain (20) 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 $2\mathcal{V}$.

Trade volume, $\mathcal{V}$, depends on the nominal rate ι (or equivalently, inflation μ), and dealers' market power θ indirectly, through the general equilibrium effect on ε^*. A decrease in ι or an increase in θ increases the expected return to holding money, which makes more investors willing to sell equity for money in the OTC market, i.e., ε^* increases and so does trade volume. In other words, the increase in *turnover liquidity* caused by the increase in ι or θ manifests itself through an increase in trade volume. 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 6 *In the stationary monetary equilibrium: (i) $\partial\mathcal{V}/\partial\mu < 0$ and $\partial\mathcal{V}/\partial\iota < 0$, and (ii) $\partial\mathcal{V}/\partial\theta > 0$ and $\partial\mathcal{V}/\partial\alpha > 0$.*

5.2.3 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 $k_t(\boldsymbol{a}_t, \varepsilon)$ 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 stationary 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 $\bar{\mathcal{S}} = \int \left[\mathcal{S}^a(\varepsilon)\,\mathbb{I}_{\{\varepsilon^*<\varepsilon\}} + \mathcal{S}^b(\varepsilon)\,\mathbb{I}_{\{\varepsilon<\varepsilon^*\}}\right] dG(\varepsilon)$. The change $\bar{\mathcal{S}}$ in response to changes in μ or α is ambiguous in general.[9]

5.3 Speculative premium

According to Proposition 2, 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.,

[9]The 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 $\mu \in (\bar{\beta}, \hat{\mu})$, it is easy to show $\partial\mathcal{S}^a(\varepsilon)/\partial\varepsilon^* = -\partial\mathcal{S}^b(\varepsilon)/\partial\varepsilon^* < 0$.

$\hat{\phi}_t^s \equiv \left[\bar{\beta}\delta/(1-\bar{\beta}\delta)\right]\bar{\varepsilon}y_t$. 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.[10] 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

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

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

[10] It 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 label used by Harrison and Kreps (1978) to avoid semantic controversies.

Proposition 7 *In the stationary monetary equilibrium: (i) $\partial \mathcal{P}/\partial \mu < 0$ and $\partial \mathcal{P}/\partial \iota < 0$, and (ii) $\partial \mathcal{P}/\partial (\alpha\theta) > 0$.*

Together, Proposition 6 and Proposition 7 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. The 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).

6 Empirical results

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 3). The mechanism through which the increase in the nominal rate is transmitted to the asset price is the reduction in *turnover liquidity* evidenced in a reduction in trade volume (part (i) of Proposition 6). These two theoretical results suggest two hypotheses that can be tested with asset pricing and turnover data: (a) surprise increases in the nominal rate reduce real stock returns, and (b) the mechanism operates through a reduction in turnover liquidity (e.g., as measured by trade volume).

6.1 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). 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., $\mathcal{T}_t^s = \mathcal{V}_t^s / A_t^s$, 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.

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 (Federal Open Market Committee) policy announcement, as in Rigobon and Sack (2004).[11] Specifically, we use the 3-month Eurodollar futures rate produced by the CME Group (Chicago Mercantile Exchange Group) and supplied by Datastream. In some of our empirical exercises, 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 on FOMC announcement days. The sample we analyze runs from January 3, 1994 to November 26, 2001.[12] The sample includes between 1300 and 1800 stocks (depending on the time period) and 73 policy dates.[13]

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 6.2, we estimate these effects for policy announcement days for a broad index of stocks. In Subsection 6.3, we document that the strength of the effect of monetary policy on stock returns differs

[11]Eurodollar 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.

[12]We choose to end the sample period in 2001 because our theory abstracts from credit, and credit conditions in the U.S. financial market appear to have eased dramatically in the six years leading up to the 2007 financial crisis. For example, the private-label securitization market grew in issuance from under $500 billion to over $2 trillion in 2006, the year before the crisis; see e.g., Gorton and Metrick (2012). However, in Appendix B (Section B.5), we extend the empirical analysis to the sample period 1994-2007. We 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.

[13]Our full sample contains 78 policy dates, but we follow Rigobon and Sack (2004) and discard five of these policy dates because they are preceded by either one or two holidays in financial markets. Those observations are needed because one of our procedures requires data involving first differences in variables on the policy day and on the day preceding the policy day.

systematically with the turnover liquidity of the stock. In Subsection 6.4, we go a step further and estimate the dynamic effects of the policy announcement on returns and turnover.

6.2 Aggregate announcement-day effects

The empirical literature has followed several approaches to estimate the impact of monetary policy surprises on the stock market on the day of a policy announcement. 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 monetary policy 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:

$$Y_t^I = a + b\Delta i_t + \epsilon_t \tag{21}$$

for $t \in S_1$, with $Y_t^I = \mathcal{R}_t^I$, where ϵ_t is an exogenous shock to the asset price.[14] We refer to the estimator b as the *event-study estimator* (or "E-based" estimator, for short).

A concern with (21) 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 consider the *heteroskedasticity-based estimator* ("H-based" estimator, for short) proposed by Rigobon and Sack (2004). The derivation of the H-based estimator is discussed in Appendix B (Section B.1). In Appendix B (Section B.2), we also consider 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. By focusing on changes in a proxy for the policy rate in a very narrow 30-minute window around the time of the policy announcement, this 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.

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

[14] In 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).

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 equity returns to monetary policy. The point estimate for b in (21) is -3.77. This means that a 1 basis point (bp) increase in the policy rate causes a decrease of 3.77 basis points (bps) in the stock market return on the day of the policy announcement.[15] The analogous H-based point estimate is -6.18, implying that a 25 bp increase in the policy rate causes a decrease in the stock market return of 1.54 percentage points (pps) on the day of the policy announcement. These results are in line with those reported in previous studies.[16] The HFIV point estimate is also negative, and the magnitude is larger than the E-based and H-based estimates.[17]

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 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 assess this theoretical mechanism, we again estimate b in (21) (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 (instead of the average stock return, $\mathcal{R}_t^I$).

The estimated effects of monetary policy announcements on the turnover rate are reported in the second row of Table 1. According to the event-based estimate, a 1 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 $-.000025$.[18] The daily marketwide turnover rate for our sample period is .0037 (i.e., on average, stocks turn over .94 times during a typical year composed of 252

[15]The R^2 indicates that 16 percent of the variance of equity prices in days of FOMC policy announcements is associated with news about monetary policy.

[16]The 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.

[17]Note, however, that due to data availability, the HFIV estimation is based on 64 policy dates used for the E-based and H-based estimations.

[18]The R^2 indicates that 15 percent of the variance of the daily turnover rate in days of FOMC policy announcements is associated with unexpected changes in monetary policy.

trading days), which means that 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 17 percent of its typical level. The heteroskedasticity-based estimate for a 1 bp increase in the policy rate is $-.000045$, implying that a 25 bp increase in the policy rate causes a reduction in the marketwide turnover rate of about 30 percent of its typical level. The HFIV estimate is similar.

6.3 Disaggregative announcement-day effects

Another way to provide direct evidence of the turnover-liquidity transmission mechanism of monetary policy is to exploit the cross-sectional variation in turnover rates across stocks. Our theory implies that the magnitude of the change in the stock return induced by a change in the policy rate will tend to be larger for more liquid stocks (i.e., stocks with a higher turnover rate). To test this prediction, we sort stocks into portfolios according to their turnover liquidity, as follows. For each policy announcement date, t, we calculate $\mathcal{T}_t^s$ as the average turnover rate of an individual stock s over all the 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 $i = 1, ..., 20$. Hence, the average turnover rate over the four-week period prior to the announcement date for a stock in i^{th} portfolio is at least as large as that of a stock in $(i-1)^{\text{th}}$ portfolio. In Table 2, the column labeled "Turnover" reports the annual turnover rate (based on a year with 252 trading days) corresponding to each of the 20 portfolios. For example, portfolio 1 turns over .11 times per year while portfolio 20 turns over 3.11 times per year.[19]

For each of the 20 portfolios, the columns in Table 2 labeled "E-based" report the event-study estimates of the responses (on the day of the policy announcement) of the return and turnover of the portfolio to a 1 percentage point (pp) increase in the policy rate. All the estimates in the column labeled "Return" are negative, as predicted by the theory. Also as predicted by the quantitative theory, the magnitude of the (statistically significant) estimates increases with the turnover liquidity of the portfolio. For example, a 1 bp increase in the policy

[19] Our 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.

rate causes a decrease of 2.03 bps in the return of portfolio 1 and a decrease of 6.27 bps in the return of portfolio 20. Fourteen of the E-based estimates in the column labeled "Turnover" are negative and statistically significant (at the 5 percent level), as predicted by the theory. Also as predicted by the quantitative theory, the magnitude of the (statistically significant) estimates increases with the turnover liquidity of the portfolio. For example, based on the point estimates, the magnitude of the response of the turnover rate of portfolio 20 is about twelve times larger than that of portfolio 2.

In Table 2, the columns labeled "H-based" report the H-based estimates of the responses (on the day of the policy announcement) of the return and turnover of each of the 20 portfolios to a 1 pp increase in the policy rate. The magnitudes of the H-based estimates tend to be larger than the E-based estimates. The sign and ranking of the H-based estimates across portfolios are roughly in line with the predictions of the theory. All the coefficients in the column labeled "Return" are negative, and the magnitude of the (statistically significant) estimates tends to increase with the turnover liquidity of the portfolio. For example, a 1 bp increase in the policy rate causes a decrease of 3.4 bps in the return of portfolio 1 and a decrease of 12 bps in the return of portfolio 20. Fifteen of the coefficients in the column labeled "Turnover" are negative and statistically significant (at the 5 percent level), as predicted by the theory. Also, the magnitude of the (statistically significant) coefficients tends to increase with the turnover liquidity of the portfolio.[20] For example, the response of the turnover rate of portfolio 20 is about twelve times larger than the response of the turnover rate of portfolio 2.

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 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

[20] In 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.

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 we fit is

$$\begin{aligned}\mathcal{R}_t^s &= \beta_0 + \beta_1 \Delta i_t + \beta_2 \mathcal{T}_t^s + \beta_3 \overline{\mathcal{T}_t^s} \times \overline{\Delta i_t} \\ &\quad + D_s + D_t + \beta_4 (\Delta i_t)^2 + \beta_5 (\mathcal{T}_t^s)^2 + \varepsilon_{st}, \end{aligned} \tag{22}$$

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 the theoretical prediction that increases (reductions) in the policy rate cause larger reductions (increases) in returns of stocks with a larger turnover rate, i.e., the quantitative theory predicts $\beta_3 < 0$.

Table 3 reports the results from estimating five different specifications based on (22). 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 estimate of β_1 is about -2.4 in specifications (I)-(V), implying that a 1 bp increase in the policy rate reduces the return of a stock with average turnover by 2.4 bps on the day of the policy announcement.[21] Combined, the estimates of β_1 and β_4 in specifications (VI)-(IX) imply a stronger response of stock returns to the policy rate. For example, according to specification (IX), a 1 bp increase in the policy rate reduces the return of a stock with average turnover by 5.6 bps on the day of the policy announcement. The sign and magnitude of the estimates lie within the range of responses reported in Table 1.

The estimate of interest, β_3, is large and negative in all specifications, ranging from -415

[21]Recall the average daily turnover in our sample is .0037.

(specification (VII)) to -100 (specification (IV)). The negative and statistically significant estimates of β_3 indicate that the magnitude of the negative effect of 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 an equity A with a turnover rate equal to 94.679 bps (i.e., an equity in the 95$^{\text{th}}$ percentile of turnover rates of the sample) and an equity B with a turnover rate equal to 5.975 bps (i.e., in the 5$^{\text{th}}$ percentile of turnover rates). Then, for example according to specification (IX), the estimate of β_3 is -410, implying that a 1 bp increase in the policy rate reduces the announcement-day return by $\beta_1+2\beta_4+\beta_3\left(\mathcal{T}_t^A-\mathcal{T}\right)\approx-4$ bps for equity A and by $\beta_1+2\beta_4+\beta_3\left(\mathcal{T}_t^B-\mathcal{T}\right)\approx-.34$ bps for equity B. Together with the findings reported in Table 1 and Table 2, these results provide additional evidence that turnover liquidity is a quantitatively important channel that transmits monetary policy shocks to asset prices.

6.4 Dynamic effects

In the previous section, we have 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 future stock turnover. 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 during 1994-2001.

The baseline VAR we estimate consists of three variables, i.e., $\left\{i_t,\mathcal{R}_t^I,\mathcal{T}_t^I\right\}$, 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 6.1 and Section 6.2.[22] The lag length is set to 10.[23] To identify the effects of

[22]In Section 6.2, 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 Eurodolar futures rate, and the results for returns and turnover are quite similar.

[23]The 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 of the theoretical impulse responses implied by our

monetary policy shocks, we apply an identification scheme based on an external high-frequency instrument.[24]

Figure 2 reports the impulse responses of the policy rate, the average stock return, and the average turnover rate, to a 1 bp increase in the policy rate. The 95 percent confidence intervals are computed using a recursive wild bootstrap based on 10,000 replications.[25] The top and bottom rows show responses for forecast horizons of 30 days and 120 days, respectively. The path of the policy rate is quite persistent; it remains significantly above the level prevailing prior to the shock for about one year. The middle panels in Figure 2 show the response of daily stock returns. On impact, in response to the 1 bp unexpected increase in the nominal rate, the stock return falls by about 7 bps (the 95 percent confidence band ranges from -8.03 to -6.24 bps). Notice that the size and magnitude of this decrease in the stock return on the day of the policy shock are in line with the estimates reported in Table 1. The negative effect on the stock return is relatively short-lived: it becomes statistically insignificant about two days after the policy shock, and according to the point estimates, it takes about 1 day to recover half of the initial drop. The right panels in Figure 2 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 $-.000038$ (the 95 percent confidence band ranges from $-.000047$ to $-.000035$), which is similar to the H-based and HFIV point estimates reported in Table 1. According to the point estimates, 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 is quite persistent (e.g., it takes about 50 days for it to become statistically insignificant).

Bernanke and Kuttner (2005) is one of the few papers that tries 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 that the component associated with future excess returns accounts for the largest part of the response of stock prices to changes in the nominal rate. This means that an increase in the policy rate lowers stock prices mostly by

quantitative theory (see Appendix B, Section B.4.3, for details).

[24]See 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).

[25]The procedure to calculate the confidence intervals is described in Appendix B (Section B.4.2). See Gonçalves and Kilian (2004) for a formal econometric analysis of this method.

increasing the expected equity premium. Bernanke and Kuttner speculate that 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. In this section, we have provided empirical evidence for the novel mechanism suggested by our theory, i.e., that (at least part of) this increase in future stock returns comes about because tight money reduces the *turnover liquidity* of stocks (as measured by the stock turnover rate). Specifically, a higher nominal rate makes the payment instruments (e.g. real bank reserves, real money balances) more scarce, which reduces the resalability and turnover, and this increased illiquidity is reflected in a reduction of the equity price. In Appendix B (Section B.4.5), we carry out the same VAR analysis of this section on each of the 20 liquidity portfolios constructed in Section 6.3 and find that—as predicted by the quantitative theory—the strength and persistence of the responses to nominal rate shocks are larger for portfolios with larger turnover liquidity.

7 Quantitative analysis

The theoretical result we used to motivate these regressions of Section 6 (i.e., part (i) of Proposition 3 and part (i) of Proposition 6) is akin to an experiment consisting of a permanent and entirely unanticipated increase in the nominal rate, so while suggestive, it is not a theoretical experiment that corresponds exactly to the empirical estimates we reported in Section 6. In order to properly 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. Specifically, we simultaneously extend the model in two directions. First, we incorporate aggregate uncertainty regarding the path of monetary policy (implemented through changes in the nominal interest rate). 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 to the case of multiple assets 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 asset returns and turnover.

7.1 Generalized model

There are N asset classes, each indexed by $s \in \mathbb{N} = \{1, 2, ..., N\}$. The outstanding quantity of equity shares of class s is A^s. Since the focus is on the implication of liquidity differences across asset classes, we assume each asset 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 asset 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 asset class $s \in \mathbb{N}$ with probability $\alpha^s \in [0, 1]$. The event that the investor is able to trade asset class s is independent of the event that he is able to trade any other asset class $n \in \mathbb{N}$. We interpret α^s as the probability that an individual investor contacts a dealer with whom he can trade asset class s. This captures the idea that dealers are specialized in trading a particular asset class.[26] In the OTC trading round there are N competitive interdealer markets, one for each asset class. These markets are segmented in the following sense: (i) in the OTC trading round, asset 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 N portfolios, i.e., each agent chooses $\{a_t^{ms}\}_{s\in\mathbb{N}}$, where a_t^{ms} is the amount of money the investor will have available to trade asset 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 asset classes he will be able to trade, and before learning his individual valuation of the dividend (the two latter 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 of generality, 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 $\mu \in \mathbb{R}_{++}$. Here we instead assume $A_{t+1}^m = \mu_t A_t^m$, where $\{\mu_t\}_{t=1}^{\infty}$ follows a Markov chain

[26] In 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 9, 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 be different depending on whether assets differ in α or θ, however.

with $\sigma_{ij} = \Pr(\mu_{t+1} = \mu_j | \mu_t = \mu_i)$ and $\mu_i \in \mathbb{R}_{++}$ for all $i, j \in \mathbb{M} = \{1, \ldots, M\}$. The realization of μ_t is known at the beginning of period t. As before, money is injected via lump-sum transfers to investors in the second subperiod of every period.

We specialize the analysis to recursive equilibria in which prices and portfolio decisions are time-invariant functions of the aggregate state, $\boldsymbol{x}_t = (A_t^m, y_t, \mu_t) \in \mathbb{R}_+^3$. That is, $\phi_t^s = \phi^s(\boldsymbol{x}_t)$, $\bar{\phi}_t^s = \bar{\phi}^s(\boldsymbol{x}_t)$, $\phi_t^m = \phi^m(\boldsymbol{x}_t)$, $p_t^s = p^s(\boldsymbol{x}_t)$, and $\varepsilon_t^{s*} = \varepsilon^{s*}(\boldsymbol{x}_t)$. We conjecture that the recursive equilibrium has the property that real prices are linear functions of the aggregate dividend, i.e., suppose $\boldsymbol{x}_t = (A_t^m, y_t, \mu_i)$, then $\phi^s(\boldsymbol{x}_t) = \phi_i^s y_t$, $\bar{\phi}^s(\boldsymbol{x}_t) \equiv p^s(\boldsymbol{x}_t)\,\phi^m(\boldsymbol{x}_t) = \bar{\phi}_i^s y_t$, $\phi^m(\boldsymbol{x}_t)\,A_t^m = Z_i y_t$, $\varepsilon^{s*}(\boldsymbol{x}_t) \equiv \left[\bar{\phi}^s(\boldsymbol{x}_t) - \phi^s(\boldsymbol{x}_t)\right]/y_t = \bar{\phi}_i^s - \phi_i^s \equiv \varepsilon_i^{s*}$, and $A_t^{ms} = \lambda_i^s A_t^m$, 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 s in the OTC round of period t. In Appendix C (Section C.2), we show that an equilibrium is characterized by a vector $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s\}_{i\in\mathbb{M}, s\in\mathbb{N}}$ of $M(3N+1)$ unknowns that solves the following system of $M(3N+1)$ equations:

$$\phi_i^s = \bar{\beta}\delta \sum_{j\in\mathbb{M}} \sigma_{ij} \left[\bar{\varepsilon} + \phi_j^s + \alpha^s\theta \int_{\varepsilon_L}^{\varepsilon_j^{s*}} (\varepsilon_j^{s*} - \varepsilon) dG(\varepsilon)\right] \text{ for all } (i,s) \in \mathbb{M}\times\mathbb{N} \tag{23}$$

$$Z_i = \frac{\bar{\beta}}{\mu_i} \sum_{j\in\mathbb{M}} \sigma_{ij} \left[1 + \alpha^s\theta \int_{\varepsilon_j^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_j^{s*}}{\varepsilon_j^{s*} + \phi_j^s} dG(\varepsilon)\right] Z_j \text{ for all } (i,s) \in \mathbb{M}\times\mathbb{N} \tag{24}$$

$$\lambda_i^s Z_i = \frac{G(\varepsilon_i^{s*})\,A^s}{1 - G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s) \text{ for all } (i,s) \in \mathbb{M}\times\mathbb{N} \tag{25}$$

$$1 = \sum_{s\in\mathbb{N}} \lambda_i^s \text{ for all } i \in \mathbb{M}. \tag{26}$$

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 6. Before doing so, it is useful to define the theoretical analogues to 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 $\bar{\phi}_t^s \equiv p_t \phi_t^m = \phi_t^s + \varepsilon_t^* y_t$ is the *cum dividend price* of equity at date t defined in Section 4. In a recursive equilibrium, suppose the state is $\boldsymbol{x}_t = (A_t^m, y_t, \mu_i)$ at t, and $\boldsymbol{x}_{t+1} = (\mu_i A_t^m, y_{t+1}, \mu_j)$ at $t+1$, then

$$\mathcal{R}_{t+1}^s = \frac{\phi_j^s + \varepsilon_j^{s*}}{\phi_i^s} \frac{y_{t+1}}{y_t} - 1.$$

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 6.1. 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* turnover rate.[27] In a recursive equilibrium, suppose the state at date t is $\boldsymbol{x}_t = (A_t^m, y_t, \mu_i)$, then the turnover rate can be written as $\mathcal{T}_i^s = 2\alpha^s G(\varepsilon_i^{s*}) \kappa$.

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.

Let $\psi^b(\boldsymbol{x}_t)$ denote the state $\boldsymbol{x}_t$ real price of an illiquid one-period pure discount nominal bond in the second subperiod of any period (the bond is illiquid in the sense that it cannot be traded in the OTC market).[28] The Euler equation for this asset is $\psi^b(\boldsymbol{x}_t) = \beta \mathbb{E}[\phi^m(\boldsymbol{x}_{t+1}) | \boldsymbol{x}_t]$. The dollar price of the asset in the second subperiod of period t is $q(\boldsymbol{x}_t) \equiv \psi^b(\boldsymbol{x}_t)/\phi^m(\boldsymbol{x}_t)$, so the Euler equation can be written as $q(\boldsymbol{x}_t) = \beta/\bar{\pi}(\boldsymbol{x}_t)$, where $\bar{\pi}(\boldsymbol{x}_t) \equiv \frac{\phi^m(\boldsymbol{x}_t)}{\mathbb{E}[\phi^m(\boldsymbol{x}_{t+1})|\boldsymbol{x}_t]}$. Then the (net) nominal rate on this bond (between period t and period $t+1$) is $r(\boldsymbol{x}_t) \equiv q(\boldsymbol{x}_t)^{-1} - 1 = \bar{\pi}(\boldsymbol{x}_t)/\beta - 1$. Suppose $\boldsymbol{x}_t = (A_t^m, y_t, \mu_i)$, then in a recursive equilibrium, $\bar{\pi}(\boldsymbol{x}_t) \equiv \bar{\pi}_i$ and $r(\boldsymbol{x}_t) \equiv r_i = \bar{\pi}_i/\beta - 1$, where $\bar{\pi}_i = \frac{\mu_i}{\bar{\gamma}} \frac{Z_i}{\sum_{j\in\mathbb{M}} \sigma_{ij} Z_j}$. So the one-period risk-free nominal interest rate between time t in state $\boldsymbol{x}_t = (A_t^m, y_t, \mu_i)$ and time $t+1$ is

$$r_i = \frac{\mu_i}{\bar{\beta}} \frac{Z_i}{\sum_{j\in\mathbb{M}} \sigma_{ij} Z_j} - 1. \tag{27}$$

[27] The first column labeled "Turnover" in Table 2 reports the annual turnover rates corresponding to each of the 20 portfolios we studied in Section 6.3. 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 $\kappa < 1$.

[28] To simplify the exposition, here we consider the nominal interest on a hypothetical bond that is not actually traded. In Appendix C (Section C.3) we develop an extension where the monetary authority can also inject or withdraw money via explicit open-market operations involving risk-free nominal government bonds. Proposition 10 (in Appendix C, Section C.3) establishes that the simpler environment presented here can be interpreted formally as a reduced-form of the richer environment with explicit open-market operations.

7.2 Calibration

We think of one model period as being one day. The discount factor, β, is chosen so that the annual real risk-free rate equals 3 percent, i.e., $\beta = (0.97)^{1/365}$. Idiosyncratic valuation shocks are distributed uniformly on $[0, 1]$, i.e., $G(\varepsilon) = \mathbb{I}_{\{\varepsilon_L \leq \varepsilon \leq \varepsilon_H\}}\varepsilon + \mathbb{I}_{\{\varepsilon_H < \varepsilon\}}$ with $\varepsilon_L = 0$ and $\varepsilon_H = 1$. 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 empirical liquidity portfolios we considered in the cross-sectional analysis of Section 6.3. We normalize $\alpha^{20} = 1$ and calibrate $\{\alpha^s\}_{s=1}^{19}$ and the fraction of actively traded stocks, κ, so that the following twenty moment conditions are satisfied: (a) for $s = 1, ..., 19$, the long-run time-average of the equilibrium turnover rate, i.e., $\bar{\mathcal{T}}^s \equiv \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathcal{T}_t^s$, equals the average turnover rate of the s^{th} synthetic empirical liquidity portfolio in our sample, and (b) the average equilibrium turnover rate across asset classes and time (under the invariant distribution of monetary policy shocks) equals the average turnover rate across all stocks in our sample, i.e., $\frac{1}{20}\sum_{s=1}^{20} \bar{\mathcal{T}}^s = .0037$.[29]

We set $\theta = 1$ in our baseline and abstract from micro-level pricing frictions induced by bargaining. Finally, we estimate the parameters that determine the monetary policy process, i.e., $\{\mu_i, \sigma_{ij}\}_{i,j\in\mathbb{M}}$ and M, as follows. We estimate the stochastic process for the policy rate using the rate of the 3-month Eurodollar future contract. The sample runs from January 3, 1994, to November 26, 2001. We formulate that the logarithm of the policy rate follows an AR(1) process, we estimate this process at a daily frequency, and approximate it with a 7-state Markov chain, $\{r_i, \sigma_{ij}\}_{i,j=1}^{7}$.[30] From (27), there is a one-to-one mapping between the nominal

[29] This procedure delivers $\alpha^1 = .0952$, $\alpha^2 = .1171$, $\alpha^3 = .1344$, $\alpha^4 = .1506$, $\alpha^5 = .1665$, $\alpha^6 = .1822$, $\alpha^7 = .1977$, $\alpha^8 = .2135$, $\alpha^9 = .2296$, $\alpha^{10} = .2467$, $\alpha^{11} = .2654$, $\alpha^{12} = .2849$, $\alpha^{13} = .3076$, $\alpha^{14} = .3341$, $\alpha^{15} = .3658$, $\alpha^{16} = .4051$, $\alpha^{17} = .4561$, $\alpha^{18} = .5287$, $\alpha^{19} = .6520$, and $\kappa = .03$.

[30] Specifically, the process we estimate is $\ln i_t = (1-\xi)\ln i_0 + \xi \ln i_{t-1} + \varepsilon_t$, where ε_t is Gaussian white noise. With i_t denominated in bps, the estimates are $\xi = .9997652$, $\mathbb{E}(\ln i_t) = \ln i_0 = 5.7362$, and $\sqrt{\mathbb{E}(\varepsilon_t^2)} = .0102$. Hence the estimated mean and standard deviation of the nominal rate, i_t, are $\mathbb{E}(i_t) = 346$ and $\sqrt{Var(i_t)} = 172$. The estimated AR(1) process is very persistent so, as suggested by Galindev and Lkhagvasuren (2010), we use the

rate and the money growth rate in the theory, and since the policy rate is estimated to be very persistent, we have $r_i \approx \mu_i/\bar{\beta} - 1$. Thus, the money supply process we use to simulate the model is $\{\mu_i, \sigma_{ij}\}_{i,j=1}^{7}$, where σ_{ij} are the estimated transition probabilities for the policy rate, and $\mu_i \approx \bar{\beta}(1 + r_i)$.

In the remainder of the section, we conduct three experiments to assess the ability of the theory to match the evidence documented in Section 6. In all experiments, we simulate the calibrated model as follows. First, compute the equilibrium functions characterized by (23)-(26). 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 proxy for the policy rate. 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 and turnover rate for each asset class.

7.3 Experiment 1: Aggregate announcement-day effects

The first experiment we conduct is the model analogue of the event-study regression analysis of Section 6.2. For each simulated equilibrium path for average daily stock return and turnover rate (i.e., the arithmetic average across the 20 stock classes), we run the event-study regression (21) for returns as well as for turnover.

Figure 3 displays the distribution of point estimates for the response of the daily marketwide average return to the policy rate implied by these 1,000 regressions on simulated data. The average point estimate is -2.23 (with standard deviation 1.08), which is quite close to the empirical (E-based) estimate of -3.77 obtained in Section 6.2. In fact, Figure 3 shows that -3.77 is within the 95 percent confidence interval of the point estimates generated by the theory. Regarding the model response of the turnover rate, the average point estimate in response to a 1 bp increase in the policy rate is $-.000001$, about two orders of magnitude smaller than the empirical point (E-based) estimate of $-.000025$ obtained in Section 6.2. These comparisons are limited to the announcement-day responses. As we show below, although the model response for turnover on the announcement day is relatively small, it is very persistent and tends to converge to the empirical response in subsequent days.

Rouwenhorst method to compute the approximating Markov matrix and states. The code for the Rouwenhorst method is also from Galindev and Lkhagvasuren (2010).

7.4 Experiment 2: Disaggregative announcement-day effects

The second experiment is the model analogue of the cross-sectional event-study analysis of Section 6.2. For each of the 20 asset classes, we run an event-study regression for returns and an event-study regression of turnover using the simulated equilibrium path for daily stock return and turnover rate for that particular asset class.

The results for returns are illustrated in Figure 4, which reports the empirical E-based estimates from Table 2 along with the estimates from the simulated model. For each theoretical portfolio, the value displayed in Figure 4 is the average E-based estimate over the model 1,000 simulations. The 95% confidence intervals for the theoretical estimates are constructed using the distribution of estimates from the 1,000 model simulations. The 95 percent confidence intervals for the empirical estimates are from the oridnary least squares (OLS) regressions from Section 6.3. The magnitudes of the model estimates are somewhat smaller than their empirical counterparts, but they all fall within the 95 percent confidence bands of the empirical estimates. Also, the slope of the response appears to be somewhat steeper in the data.

The results for turnover are illustrated in Figure 5, which reports the empirical E-based estimates from Table 2 along with the estimates from the simulated model. All estimates shown in the figure have been normalized by the average of the estimates across portfolios. That is, the response of each portfolio is expressed as a multiple of the average response.[31] This allows us to focus on the magnitude of the *relative* response of turnover across asset classes. For example, in both the empirical and the model regressions, the magnitude of the drop in turnover of portfolio 13 is similar to that of the average portfolio. The magnitude of the response for portfolios with turnover lower (higher) than portfolio 13 is lower (higher) than the average. The relative magnitudes of the model responses are to a large extent in line with those estimated from the data (the model only misses the particularly large relative responses of portfolios 17 through 20).

[31]For each theoretical portfolio, the value displayed in Figure 5 is the average E-based estimate over the model 1,000 simulations divided by the average response across simulations and portfolios. The 95 percent confidence intervals for the theoretical estimates are constructed using the distribution of estimates from the 1,000 model simulations. The 95 percent confidence intervals for the empirical estimates are from the OLS regressions from Section 6.3.

7.5 Experiment 3: VAR analysis

The third experiment is the model analogue of the VAR analysis of Section 6.4. For each simulated equilibrium path for average daily stock return and turnover rate (i.e., the arithmetic average across the 20 stock classes), we estimate the impulse response to a 1 bp increase in the policy rate using exactly the same procedure used to estimate the impulse responses from the data, as described in Section 6.4 and Appendix B (Section B.4).[32]

Figure 6 reports the model-generated impulse responses for the policy rate, the average stock return, and the average turnover rate to a 1 bp increase in the policy rate, along with the corresponding empirical impulse responses estimated from actual data (those described in Section 6.4). For each variable, the model-generated impulse response reported in the figure is the median of the 1,000 impulse responses estimated from the 1,000 simulated equilibrium paths. The 95 percent confidence intervals for the theoretical responses are constructed using the distribution of estimates from the 1,000 model simulations. The 95 percent confidence intervals for the empirical impulse responses are based on the recursive wild bootstrap procedure described in Appendix B (Section B.4.2). 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 panels in the middle show the response of daily stock returns. On impact, in response to the 1 bp unexpected increase in the nominal rate, the model stock return falls by -2.4 bps, which is about 35 percent of the size of the empirical estimate. Just as in the data, the negative effect of the policy rate increase on the stock return is relatively short-lived: it takes about 1 day to recover half of the initial drop. The right panels of Figure 6 show the response of the level of the daily turnover rate. On impact, in response to a 1 bp unexpected increase in the nominal rate, the turnover rate falls by $-.000001$ in the model. As in Section 7.3, the model response for turnover is much smaller than the empirical estimate ($-.000038$ according to the empirical impulse response). However, although the model response for turnover is smaller on impact, it is very persistent and tends to converge to the empirical response in subsequent days. For example, the difference between the empirical path for the turnover rate and the theoretical path becomes statistically insignificant after about 30 days. This persistent effect of

[32] In the model-based VAR exercises, we add a small noise term (drawn i.i.d. from a uniform distribution on $[-5 \times 10^{-7}, 5 \times 10^{-7}]$) to the simulated turnover rate. We do this to ensure that return and turnover are not perfectly collinear in the simulated equilibrium. Adding this noise term to the turnover rate does not alter the equilibrium conditions in any way.

policy on the turnover rate allows the model to generate a short-run response in return that is quantitatively roughly in line with the data, although the announcement-day effect on turnover is much smaller than in the data.[33]

8 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, it 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 of costly or scarce payment instruments. Having said this, we think it would be interesting to extend the theory to allow for credit arrangements. The possibility of "buying on margin," for example, could very well magnify some of the monetary mechanisms we have emphasized here. 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 some work in this direction). Third, while our empirical work has focused on stocks, the transmission mechanism we have identified is likely to be operative—and possibly even stronger and more conspicuous—in markets for other assets, such as Treasury securities and assets that trade in more frictional over-the-counter markets.

[33]Figure 7, discussed in Appendix B.4.3, shows that according to the model, the VAR procedure may be overestimating the announcement-day effect of the policy rate on turnover and underestimating the persistence of the effect.

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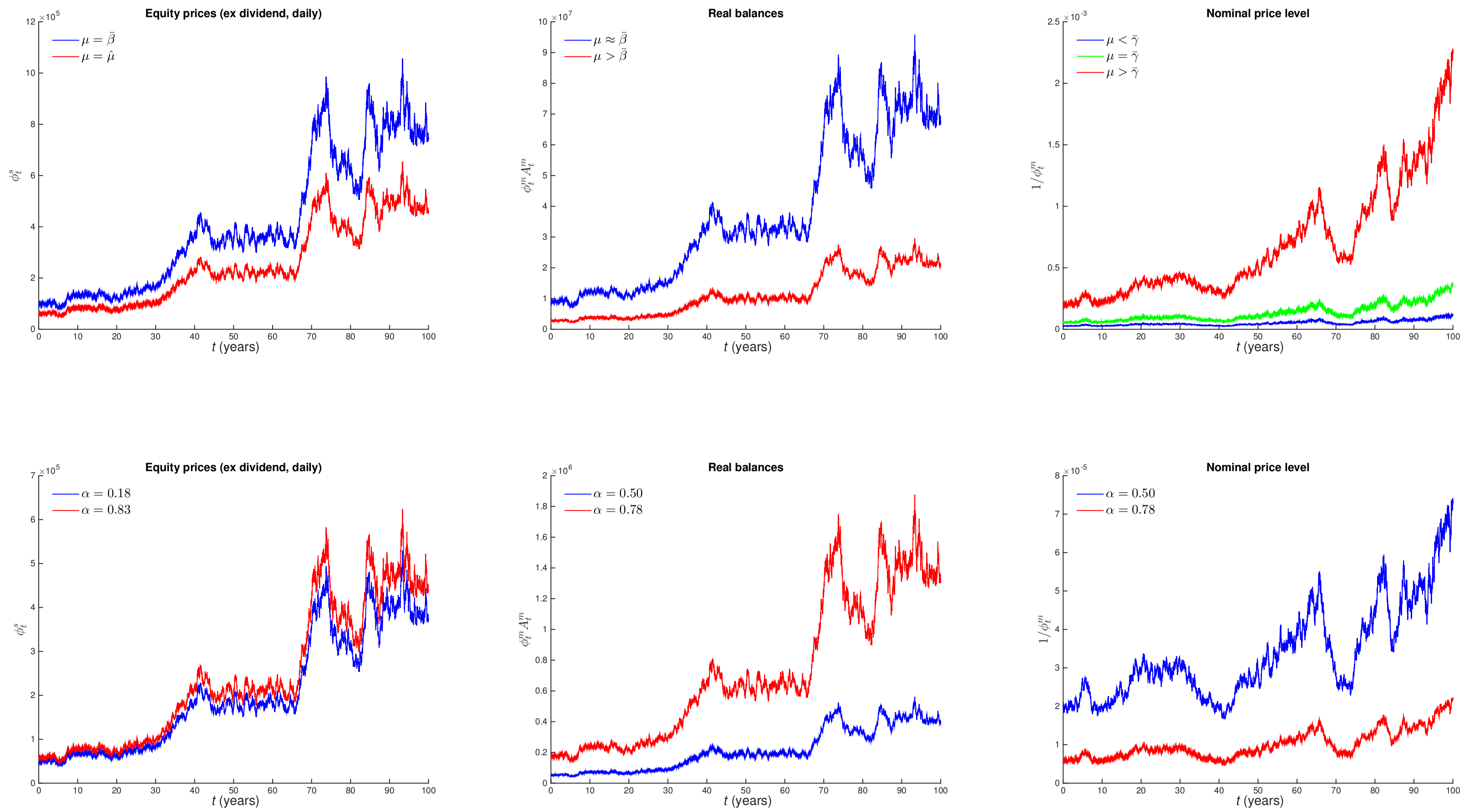

Figure 1: Effects of monetary policy and OTC frictions on asset prices.

	E-based		H-based		HFIV	
	Estimate	Std dev	Estimate	Std dev	Estimate	Std dev
Return	-3.77	1.02	-6.18	1.87	-8.57	1.69
Turnover	-.0025	.0007	-.0045	.0017	-.0043	.0009

Table 1: Empirical response of stock returns and turnover to monetary policy. All estimates are significant at the 1 percent level.

		E-based				H-based			
		Return		Turnover		Return		Turnover	
Portfolio	Turnover	Estimate	Std dev	Estimate	Std dev	Estimate	Std dev	Estimate	Std dev
1	.11	-2.03***	.73	-.0003	.0002	-3.40***	1.12	-.0008	.0005
2	.19	-1.83**	.85	-.0008**	.0004	-3.77***	1.45	-.0014**	.0006
3	.25	-1.57*	.91	-.0007	.0005	-3.02*	1.78	-.0012*	.0006
4	.31	-1.05	.87	.0002	.0007	-2.69	1.84	.0005	.0011
5	.37	-2.54**	1.03	-.0011**	.0005	-5.21**	2.43	-.0020 **	.0009
6	.42	-2.67***	1.01	-.0021**	.0009	-4.58**	1.81	-.0039***	.0013
7	.47	-3.33***	1.06	-.0016**	.0007	-6.11**	2.80	-.0031***	.0011
8	.53	-2.55**	1.12	-.0011	.0007	-4.81**	2.12	-.0024**	.0012
9	.58	-2.65**	1.20	-.0023***	.0008	-5.00**	2.45	-.0034**	.0016
10	.65	-4.33***	1.19	-.0027***	.0009	-7.25***	2.50	-.0065**	.0030
11	.71	-3.88***	1.22	-.0023***	.0009	-6.20***	2.33	-.0039***	.0014
12	.78	-3.76***	1.26	-.0030***	.0009	-5.98***	2.30	-.0059***	.0020
13	.86	-3.98***	1.15	-.0028*	.0015	-6.62***	2.40	-.0050 ***	.0019
14	.95	-4.73***	1.31	-.0034***	.0011	-7.71***	2.43	-.0061**	.0025
15	1.06	-4.69***	1.30	-.0035***	.0014	-7.61***	2.50	-.0068**	.0027
16	1.19	-5.37***	1.56	-.0037***	.0012	-9.10***	2.92	-.0066**	.0028
17	1.36	-6.02***	1.44	-.0078***	.0019	-10.50***	3.20	-.0136 ***	.0044
18	1.61	-5.21***	1.67	-.0001	.0002	-8.82***	3.01	-.0001	.0002
19	2.02	-5.93***	1.81	-.0083***	.0021	-10.57***	3.62	-.0153***	.0050
20	3.11	-6.27***	2.09	-.0088***	.0030	-12.01***	4.10	-.0172**	.0078

Table 2: Empirical responses of stock returns and turnover to monetary policy across NYSE liquidity portfolios. *** denotes significance at the 1 percent level, ** significance at the 5 percent level, * significance at the 10 percent level.

Variable	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
Δi_t	-2.52	-2.40	-2.46	-2.37	-2.44	-3.36	-3.37	-3.62	-3.63
	(.086)	(.090)	(.091)	(.097)	(.098)	(.099)	(.100)	(.110)	(.110)
$\mathcal{T}_t^s$	25.93	25.36	17.54	22.37	13.93	45.29	42.58	39.09	33.13
	(2.26)	(2.26)	(3.08)	(2.29)	(3.16)	(5.71)	(7.55)	(5.72)	(7.71)
$\overline{\mathcal{T}_t^s} \times \overline{\Delta i_t}$		-109.43	-121.14	-100.43	-111.09	-403.98	-415.17	-398.96	-410.15
		(25.36)	(25.76)	(25.28)	(25.68)	(28.22)	(28.71)	(28.06)	(28.55)
D_s			yes		yes		yes		yes
D_t				yes	yes			yes	yes
$(\Delta i_t)^2$						.947	.947	1.00	1.00
						(.041)	(.042)	(.042)	(.043)
$(\mathcal{T}_t^s)^2$						-1696.88	-1921.29	-1378.21	-1418.23
						(392.48)	(465.31)	(389.33)	(466.21)
R^2	.0084	.0086	.0085	.0314	.0316	.0132	.0132	.0363	.0364

Table 3: Effects of monetary policy on stock returns of individual stocks. Each column reports the coefficients from a separate pooled OLS regression based on (3). Number of observations: 117,487. Standard errors in parentheses. All estimates are significant at the 1 percent level.

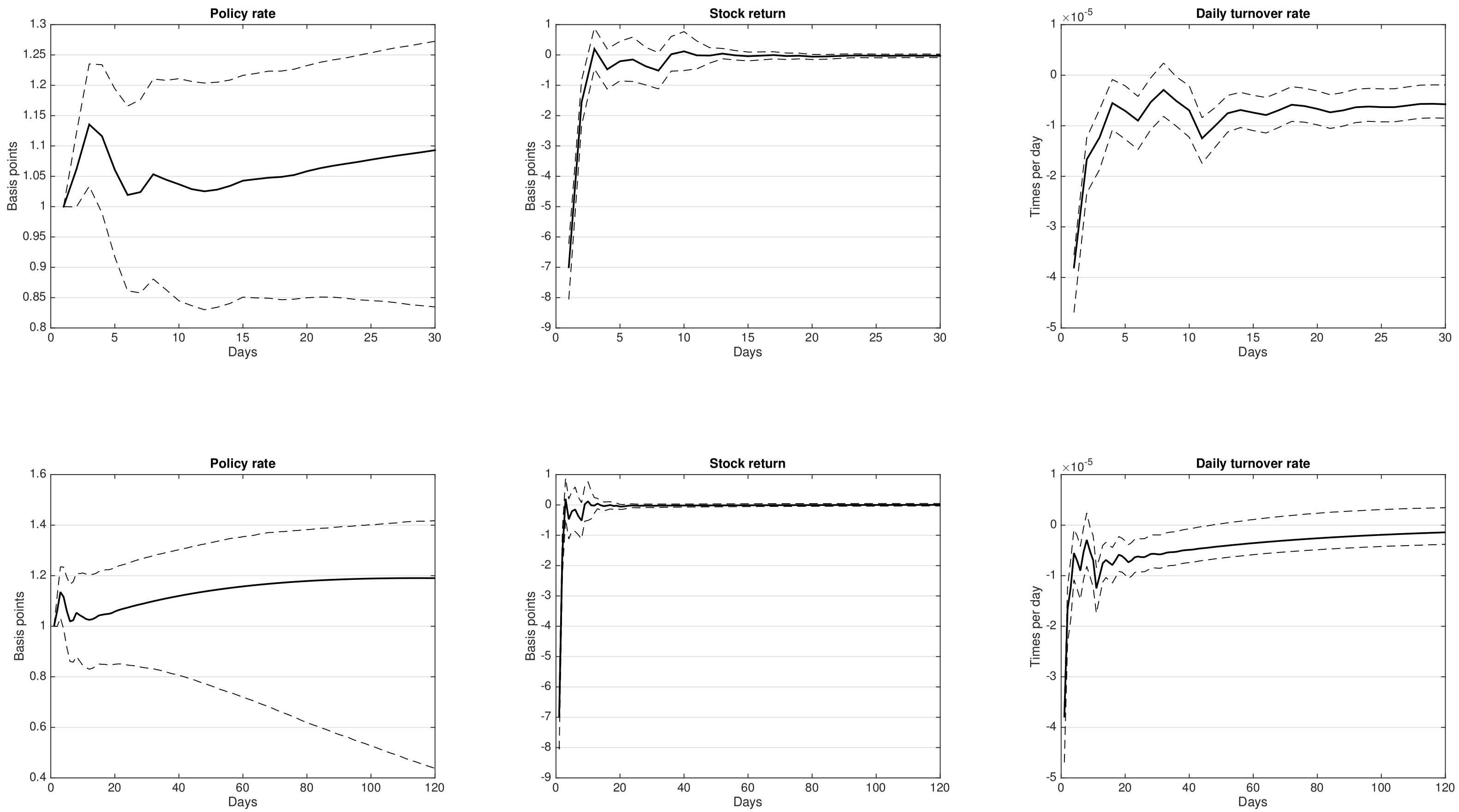

Figure 2: Empirical impulse responses to a 1 basis point increase in the policy rate. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

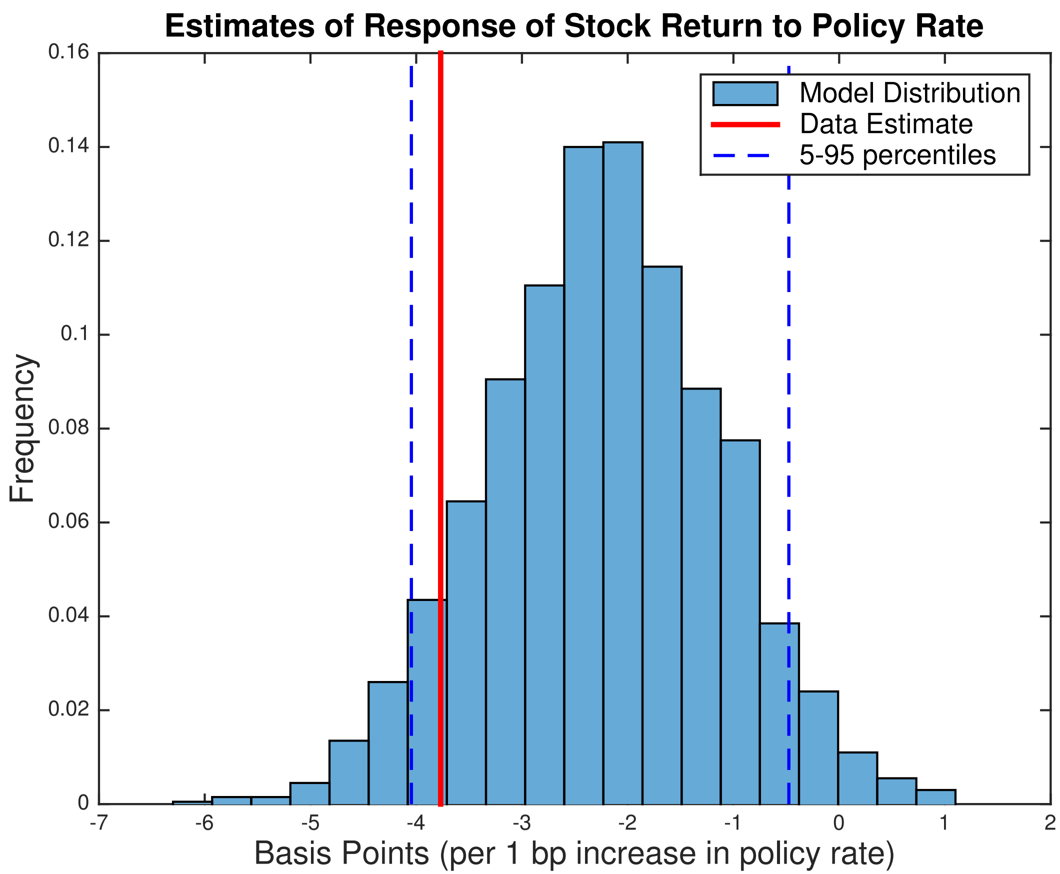

Figure 3: Estimates of announcement-day response of stock return to policy rate.

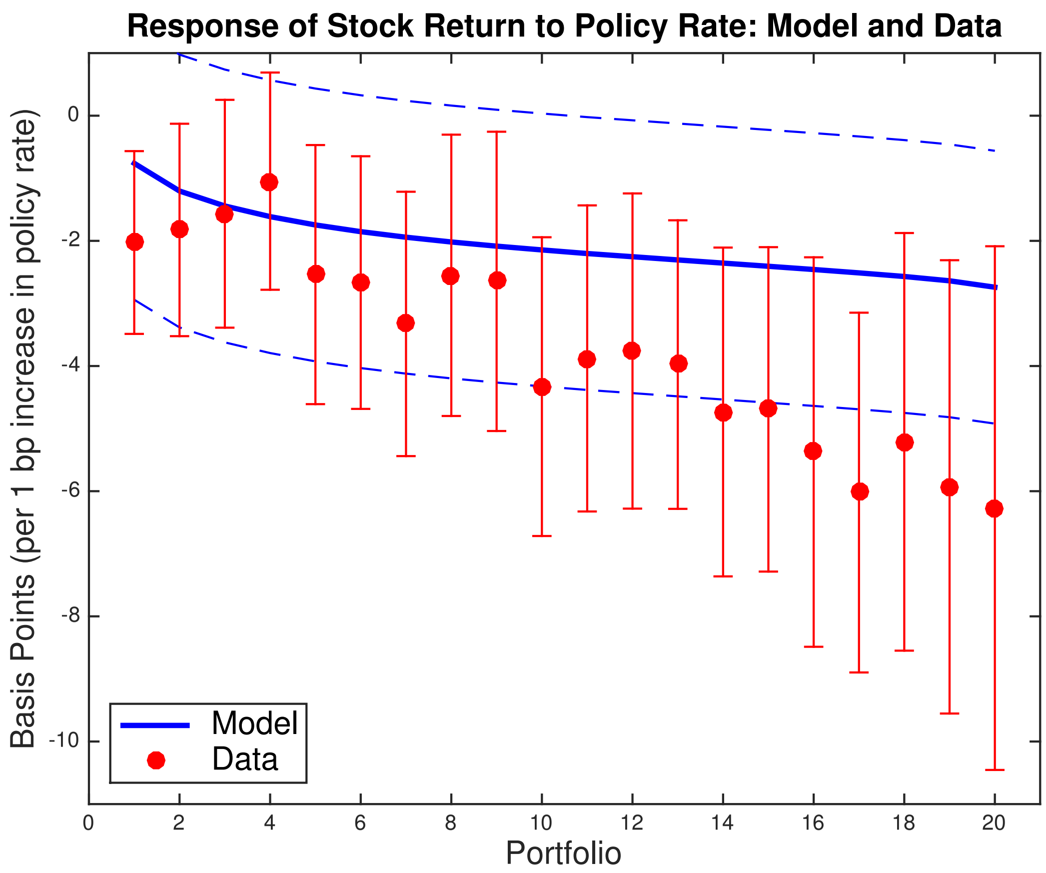

Figure 4: Cross-sectional announcement-day responses of stock returns to policy rate.

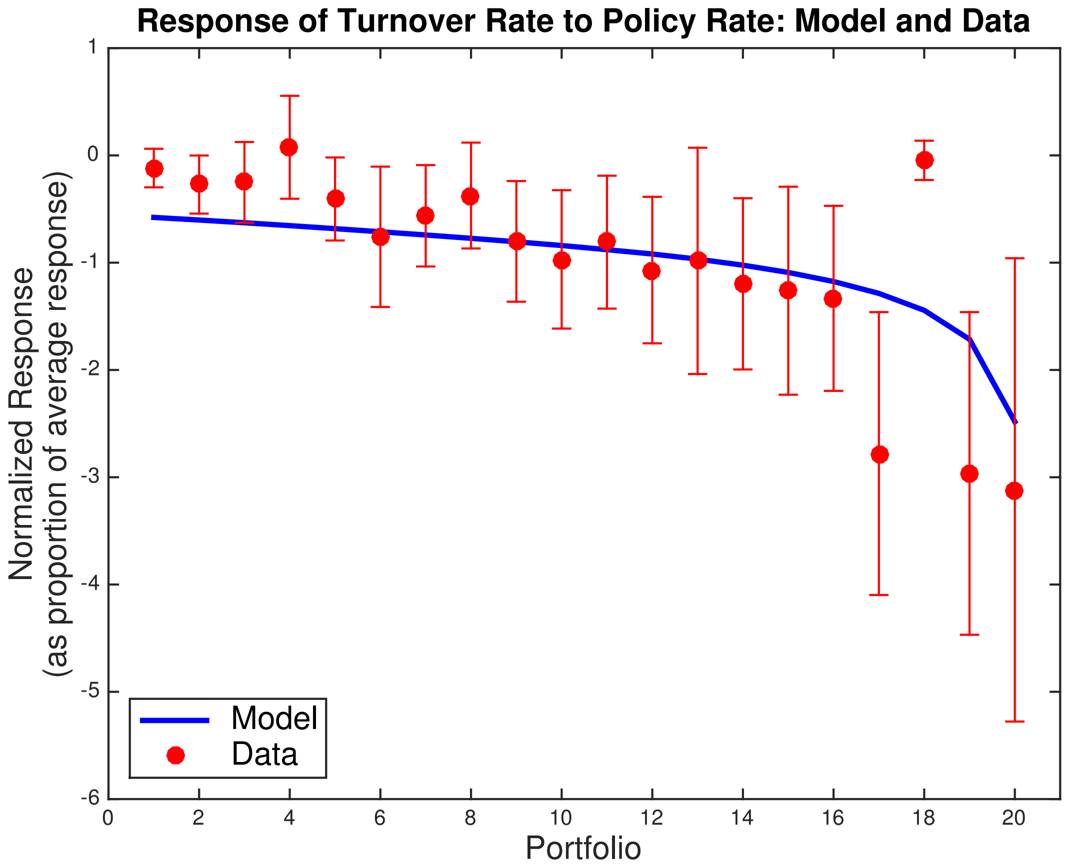

Figure 5: Cross-sectional announcement-day normalized responses of turnover rates to policy rate.

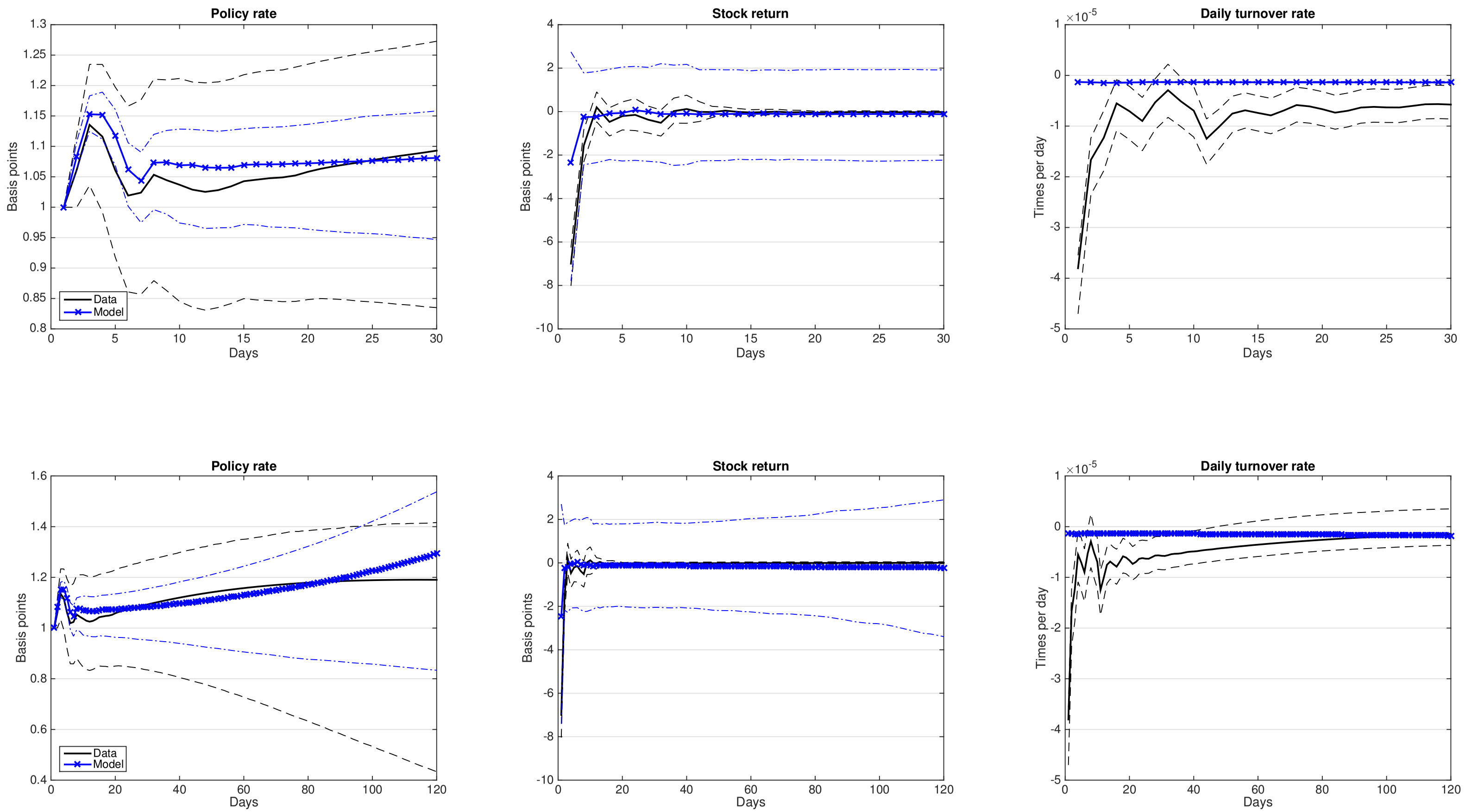

Figure 6: Impulse responses to a 1 basis point increase in the policy rate. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

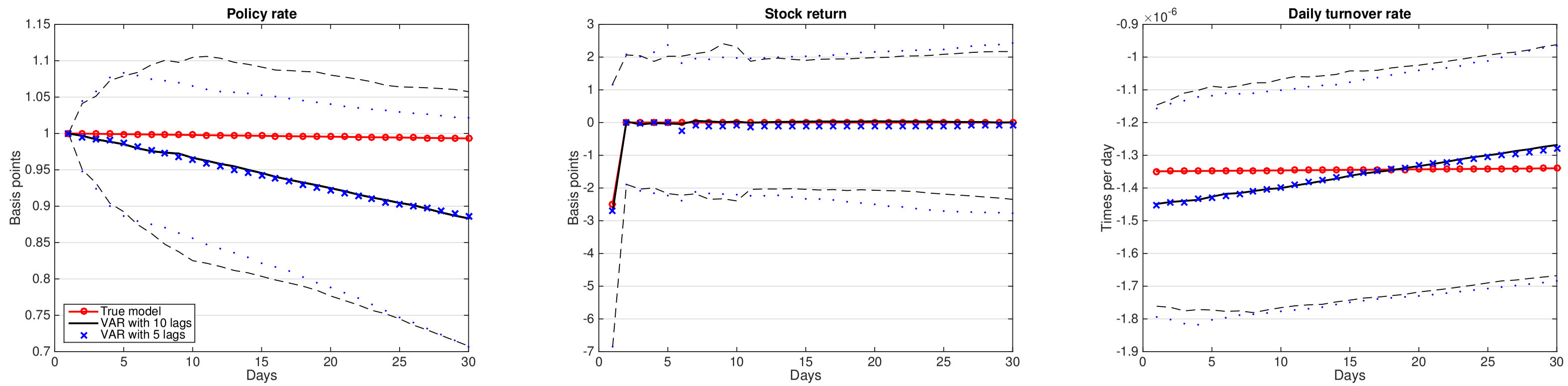

Figure 7: Impulse responses to a 1 basis point increase in the policy rate: true theoretical responses versus responses estimated from model generated data. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

		E-based		H-based		HFIV	
Portfolio	Turnover	Return	Turnover	Return	Turnover	Return	Turnover
1	.11	-2.03***	-.0003	-3.40***	-.0008	-5.80***	-.0008**
2	.19	-1.83**	-.0008**	-3.77***	-.0014**	-5.95***	-.0011**
3	.25	-1.57*	-.0007	-3.02*	-.0012*	-4.54***	-.0014**
4	.31	-1.05	.0002	-2.69	.0005	-4.29***	-.0031***
5	.37	-2.54**	-.0011**	-5.21**	-.0020 **	-5.89***	-.0017***
6	.42	-2.67***	-.0021**	-4.58**	-.0039***	-3.43**	-.0016
7	.47	-3.33***	-.0016**	-6.11**	-.0031***	-6.38***	-.0022***
8	.53	-2.55**	-.0011	-4.81**	-.0024**	-6.14***	-.0024***
9	.58	-2.65**	-.0023***	-5.00**	-.0034**	-8.02***	-.0025***
10	.65	-4.33***	-.0027***	-7.25***	-.0065**	-8.19***	-.0029***
11	.71	-3.88***	-.0023***	-6.20***	-.0039***	-6.63***	-.0036***
12	.78	-3.76***	-.0030***	-5.98***	-.0059***	-8.84***	-.0048***
13	.86	-3.98***	-.0028*	-6.62***	-.0050 ***	-11.15***	-.0036***
14	.95	-4.73***	-.0034***	-7.71***	-.0061**	-9.13***	-.00341*
15	1.06	-4.69***	-.0035***	-7.61***	-.0068**	-9.35***	-.0052***
16	1.19	-5.37***	-.0037***	-9.10***	-.0066**	-12.66***	-.0047***
17	1.36	-6.02***	-.0078***	-10.50***	-.0136 ***	-12.15***	-.0078***
18	1.61	-5.21***	-.0001	-8.82***	-.0001	-13.90***	-.0098***
19	2.02	-5.93***	-.0083***	-10.57***	-.0153***	-13.37***	-.0098***
20	3.11	-6.27***	-.0088***	-12.01***	-.0172**	-15.70***	-.0125***
NYSE	.94	-3.77***	-.0025***	-6.18***	-.0045**	-8.57***	-.0043***

Table 4: Empirical responses of stock returns and turnover to monetary policy across NYSE liquidity portfolios. *** denotes significance at the 1 percent level, ** significance at the 5 percent level, * significance at the 10 percent level.

	Return		Turnover	
Portfolio	Estimate	Std dev	Estimate	Std dev
1	-.85	1.89	-.0033	.0021
2	-2.11	1.41	-.0052***	.0019
3	-1.22	1.23	-.0052***	.0013
4	-3.38***	1.19	-.0048***	.0015
5	-2.69**	1.20	-.0036**	.0014
6	-2.68**	1.10	-.0040***	.0013
7	-2.64***	.99	-.0032**	.0014
8	-2.39**	1.06	-.0037***	.0014
9	-3.59***	1.02	-.0028*	.0015
10	-3.17***	1.03	-.0028*	.0013
11	-3.92***	1.09	-.0053***	.0016
12	-4.71***	1.05	-.0006	.0015
13	-4.41***	1.17	-.0034**	.0013
14	-6.12***	1.28	-.0025*	.0014
15	-6.53***	1.43	-.0047***	.0014
16	-6.63***	1.50	-.0032*	.0017
17	-7.25***	1.57	-.0044***	.0015
18	-6.66***	1.78	-.0055***	.0017
19	-10.16***	2.42	-.0080***	.0019
20	-13.17***	3.02	-.0082***	.0023

Table 5: Empirical responses of stock returns and turnover to monetary policy across portfolios sorted on return sensitivity to aggregate turnover (E-based estimates). *** denotes significance at the 1 percent level, ** significance at the 5 percent level, * significance at the 10 percent level.

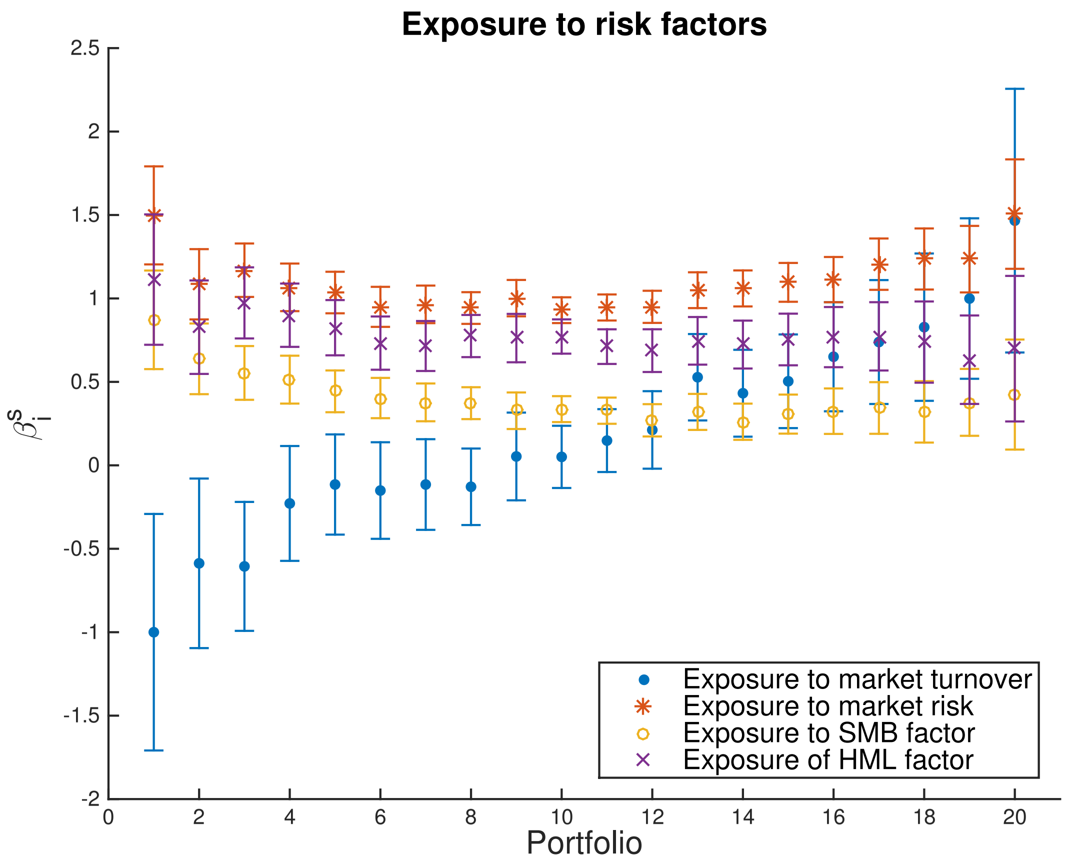

Figure 8: Betas for the 20 portfolios sorted on sensitivity of return to aggregate turnover.

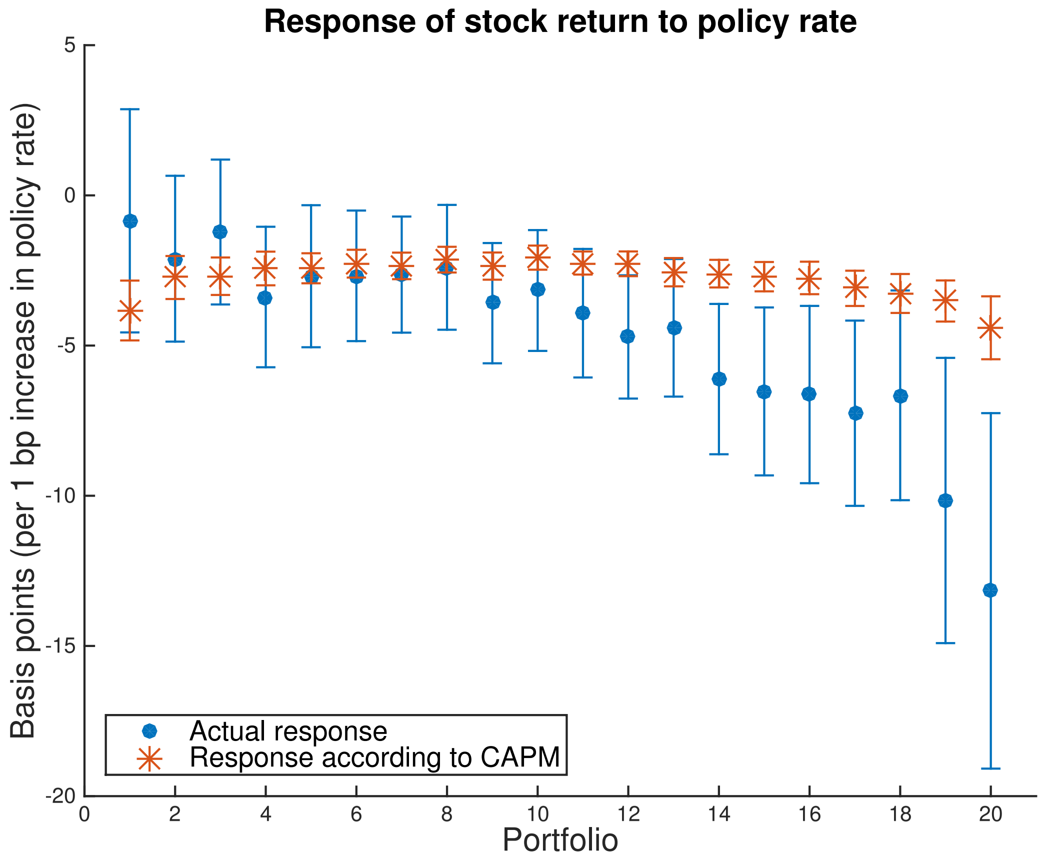

Figure 9: E-based estimates of responses of announcement-day stock returns to a 1 basis point surprise increase in the policy rate: CAPM vs. response based on portfolio analysis (for portfolios sorted on sensitivity of return to aggregate turnover).

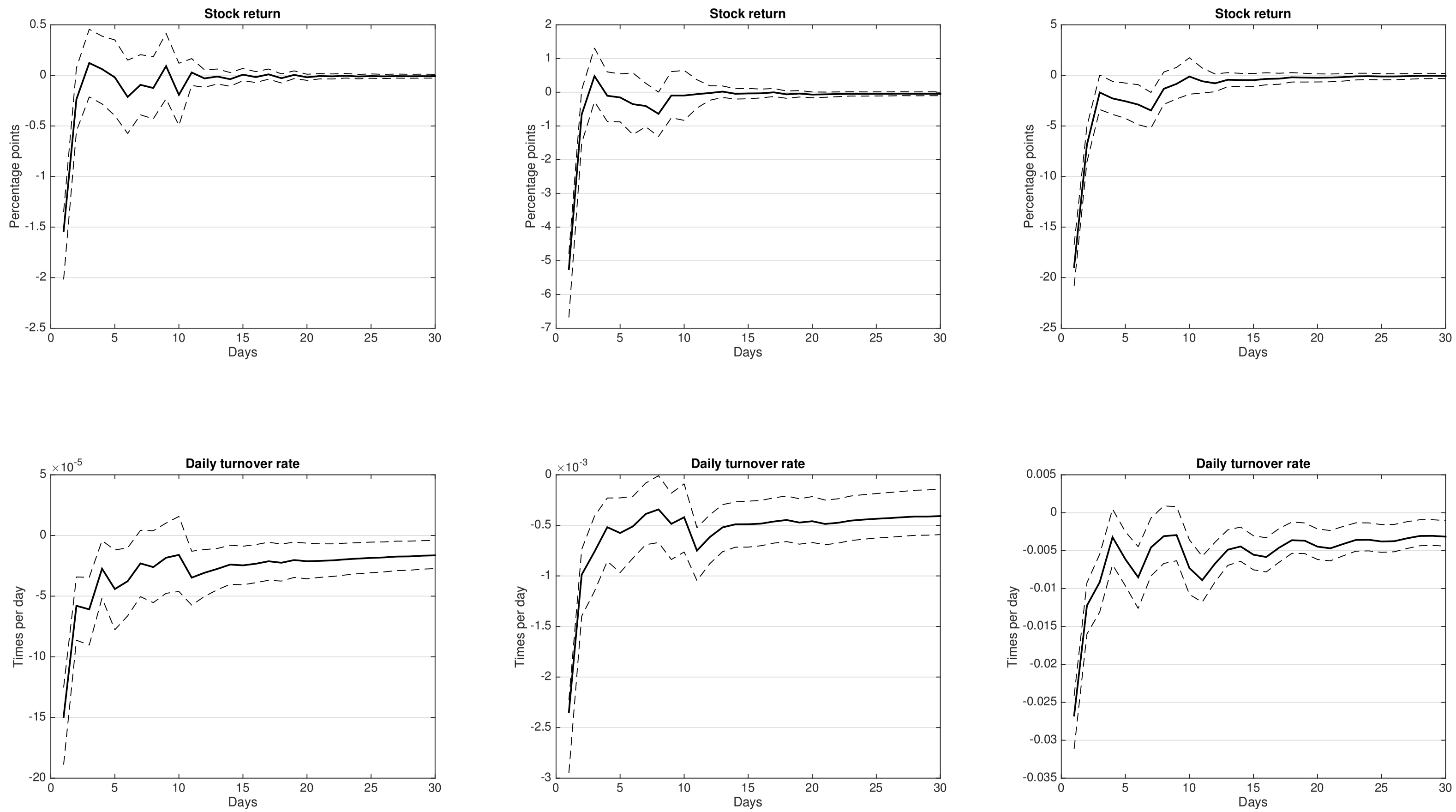

Figure 10: Impulse responses to a 1 percentage point increase in the policy rate for selected liquidity-based portfolios. The left panels correspond to portfolio 1, the middle panels to portfolio 10, and the right panels to portfolio 20. Solid lines are point estimates. Broken lines are 95 percent confidence intervals.

		E-based		H-based		HFIV	
Portfolio	Turnover	Return	Turnover	Return	Turnover	Return	Turnover
1	.18	-3.85***	-.0004	-9.75***	-.0015**	-6.25***	-.0009***
2	.35	-4.26***	-.0006	-12.13***	-.0017	-6.84***	-.0012**
3	.45	-3.60***	-.0008	-9.46***	-.0015	-5.69***	-.0022**
4	.54	-3.22***	-.0002	-11.40***	-.0012	-5.49***	-.0029***
5	.62	-4.83***	-.0010	-14.28***	-.0025	-7.23***	-.0019
6	.69	-3.65***	-.0009	-12.79***	-.0009	-5.16***	-.0018
7	.76	-4.88***	-.0008	-15.21***	-.0014	-7.33***	-.0029*
8	.84	-4.34***	-.0011	-21.28***	-.0019	-7.244***	-.0026**
9	.91	-5.10***	-.0013	-14.78***	-.0009	-8.79***	-.0030*
10	.97	-5.60***	-.0016	-16.57***	-.0040	-9.08***	-.0036*
11	1.06	-5.12***	-.0016	-14.48***	-.0025	-8.02***	-.0034
12	1.15	-5.73***	-.0022*	-17.27***	-.0047	-9.46***	-.0049***
13	1.26	-6.87***	-.0020	-18.10***	-.0038	-11.40***	-.0042***
14	1.37	-5.95***	-.0026	-18.36***	-.0026	-9.84***	-.0049**
15	1.49	-6.48***	-.0039**	-18.97***	-.0080*	-10.00***	-.0059***
16	1.66	-7.60***	-.0035*	-22.26***	-.0050	-13.25***	-.0069***
17	1.85	-7.46***	-.0035***	-21.64***	-.0042	-13.03***	-.0093***
18	2.13	-8.35***	-.0041*	-23.26***	-.0076	-14.31***	-.0096***
19	2.57	-8.33***	-.0061**	-23.74***	-.0115	-13.85***	-.0123***
20	3.63	-9.28***	-.0062	-27.55***	-.0061	-16.40***	-.0189***
NYSE	1.23	-5.73***	-.0022*	-16.79***	-.0037	-9.43***	-.0053**

Table 6: Empirical responses of stock returns and turnover to monetary policy across NYSE liquidity portfolios (1994-2007 sample). *** denotes significance at the 1 percent level, ** significance at the 5 percent level, * significance at the 10 percent level.

A Proofs

Proof of Proposition 1. The choice variable a'_{Dt} does not appear in the planner's objective function, so $a'_{Dt} = 0$ at an optimum. Also, (3) must bind for every t at an optimum, so the planner's problem is equivalent to

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

$$\text{s.t. (1), (4), (5), and } \alpha \int_{\varepsilon_L}^{\varepsilon_H} a'_{It}(d\varepsilon) \le a_{Dt} + \alpha a_{It}.$$

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

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

s.t. (1), 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 (1) (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. ■

Proof of Lemma 1. Notice that (8) implies

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

where

$$\bar{W}_t^D \equiv \max_{\tilde{\boldsymbol{a}}_{t+1} \in \mathbb{R}_+^2} \left[-\boldsymbol{\phi}_t \tilde{\boldsymbol{a}}_{t+1} + \beta \mathbb{E}_t V_{t+1}^D\left(\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s\right)\right], \tag{28}$$

so (7) implies

$$\hat{W}_t^D(\boldsymbol{a}_t, k_t) = k_t + \bar{W}_t^D + \max_{\hat{\boldsymbol{a}}_t \in \mathbb{R}_+^2} \boldsymbol{\phi}_t \hat{\boldsymbol{a}}_t$$

$$\text{s.t. } \hat{a}_t^m + p_t \hat{a}_t^s \le a_t^m + p_t a_t^s.$$

Hence,

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

$$\hat{a}_t^s(\boldsymbol{a}_t) = (1/p_t)\left[a_t^m + p_t a_t^s - \hat{a}_t^m(\boldsymbol{a}_t)\right],$$

and

$$\hat{W}_t^D(\boldsymbol{a}_t, k_t) = \max\left(\phi_t^m, \phi_t^s/p_t\right)\left(a_t^m + p_t a_t^s\right) + k_t + \bar{W}_t^D. \tag{29}$$

Also, notice that (9) implies

$$W_t^I(\boldsymbol{a}_t, -k_t) = \boldsymbol{\phi}_t \boldsymbol{a}_t - k_t + \bar{W}_t^I, \tag{30}$$

where

$$\bar{W}_t^I \equiv T_t + \max_{\tilde{\boldsymbol{a}}_{t+1} \in \mathbb{R}_+^2}\left[-\boldsymbol{\phi}_t \tilde{\boldsymbol{a}}_{t+1} + \beta \mathbb{E}_t \int V_{t+1}^I\left[\tilde{a}_{t+1}^m, \delta \tilde{a}_{t+1}^s + (1-\delta) A^s, \varepsilon\right] dG(\varepsilon)\right]. \tag{31}$$

With (29) and (30), (6) can be written as

$$\max_{\overline{a}_t^m, k_t}\left[\left(\varepsilon_t^* - \varepsilon\right)\left(\overline{a}_t^m - a_{it}^m\right)\frac{1}{p_t} y_t - k_t\right]^\theta k_t^{1-\theta}$$

$$\text{s.t. } 0 \le k_t \le \left(\varepsilon_t^* - \varepsilon\right)\left(\overline{a}_t^m - a_{it}^m\right)\frac{1}{p_t} y_t$$

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

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

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

and

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

This concludes the proof. ■

Lemma 2 *Let* $\left(\tilde{a}_{dt+1}^m, \tilde{a}_{dt+1}^s\right)$ *and* $\left(\tilde{a}_{it+1}^m, \tilde{a}_{it+1}^s\right)$ *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:*

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

$$\phi_t^s \geq \beta \delta \mathbb{E}_t \max\left(p_{t+1}\phi_{t+1}^m, \phi_{t+1}^s\right), \text{ with “} = \text{” if } \tilde{a}_{dt+1}^s > 0 \tag{33}$$

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

$$\phi_t^s \geq \beta \delta \mathbb{E}_t \left[\bar{\varepsilon} y_{t+1} + \phi_{t+1}^s + \alpha\theta \int_{\varepsilon_L}^{\varepsilon_{t+1}^*} \left(\varepsilon_{t+1}^* - \varepsilon\right) y_{t+1} dG(\varepsilon)\right], \text{ with “} = \text{” if } \tilde{a}_{it+1}^s > 0. \tag{35}$$

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

$$\begin{aligned} V_t^I(\boldsymbol{a}_t, \varepsilon) = &\left[\alpha\theta\left(\varepsilon - \varepsilon_t^*\right) \mathbb{I}_{\{\varepsilon_t^* < \varepsilon\}} \frac{1}{p_t} y_t + \phi_t^m\right] a_t^m \\ &+ \left\{\left[\varepsilon + \alpha\theta\left(\varepsilon_t^* - \varepsilon\right) \mathbb{I}_{\{\varepsilon < \varepsilon_t^*\}}\right] y_t + \phi_t^s\right\} a_t^s + \bar{W}_t^I \end{aligned} \tag{36}$$

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

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

Since ε is i.i.d. over time, $W_t^I(\boldsymbol{a}_t)$ is independent of ε, and the portfolio that each investor chooses to carry into period $t+1$ is independent of ε. Therefore, we can write $dH_{It}(\boldsymbol{a}_t, \varepsilon) = dF_{It}(\boldsymbol{a}_t)\, dG(\varepsilon)$, 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,

$$V_t^D(\boldsymbol{a}_t) = \max\left(\phi_t^m, \phi_t^s / p_t\right)\left(a_t^m + p_t a_t^s\right) + V_t^D(\mathbf{0}), \tag{37}$$

where

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

From (37) we have

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

and from (36) we have

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

where $\zeta_{t+1} \equiv \left\{ \left[\varepsilon + \alpha\theta \left(\varepsilon^*_{t+1} - \varepsilon \right) \mathbb{I}_{\left\{ \varepsilon < \varepsilon^*_{t+1} \right\}} \right] y_{t+1} + \phi^s_{t+1} \right\} (1-\delta) A^s + \bar{W}^I_{t+1}$. Thus, the necessary and sufficient first-order conditions corresponding to the maximization problems in (28) and (31) are as in the statement of the lemma. ■

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

$$\left\{ \alpha \left[1 - G\left(\varepsilon^*_t \right) \right] A^m_{It} + \chi\left(\varepsilon^*_t, 0 \right) A^m_{Dt} \right\} \frac{1}{p_t} = \alpha G\left(\varepsilon^*_t \right) A^s_{It} + \left[1 - \chi\left(\varepsilon^*_t, 0 \right) \right] A^s_{Dt}. \tag{38}$$

Proof. Recall $\bar{A}^s_{Dt} = \int \hat{a}^s_t \left(\boldsymbol{a}_t \right) dF_{Dt} \left(\boldsymbol{a}_t \right)$, so from Lemma 1, we have

$$\bar{A}^s_{Dt} = \chi\left(\varepsilon^*_t, 0 \right) \left(A^s_{Dt} + A^m_{Dt}/p_t \right).$$

Similarly, $\bar{A}^s_{It} = \alpha \int \overline{a}^s_t(\boldsymbol{a}_t, \varepsilon) dH_{It}(\boldsymbol{a}_t, \varepsilon)$, so from Lemma 1, we have

$$\bar{A}^s_{It} = \alpha \left[1 - G\left(\varepsilon^*_t \right) \right] \left(A^s_{It} + A^m_{It}/p_t \right).$$

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

Corollary 2 *A sequence of prices, $\{1/p_t, \phi^m_t, \phi^s_t\}^\infty_{t=0}$, together with bilateral terms of trade in the OTC market, $\{\overline{\boldsymbol{a}}_t, k_t\}^\infty_{t=0}$, dealer portfolios, $\{\langle \hat{\boldsymbol{a}}_{dt}, \tilde{\boldsymbol{a}}_{dt+1}, \boldsymbol{a}_{dt+1} \rangle_{d \in \mathcal{D}}\}^\infty_{t=0}$, and investor portfolios, $\{\langle \tilde{\boldsymbol{a}}_{it+1}, \boldsymbol{a}_{it+1} \rangle_{i \in \mathcal{I}}\}^\infty_{t=0}$, 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

$$\begin{aligned}
k_t \left(\boldsymbol{a}_t, \varepsilon \right) &= (1-\theta) \left(\varepsilon - \varepsilon^*_t \right) \left[\chi\left(\varepsilon^*_t, \varepsilon \right) \frac{1}{p_t} a^m_t - \left[1 - \chi\left(\varepsilon^*_t, \varepsilon \right) \right] a^s_t \right] y_t \\
\overline{a}^m_t \left(\boldsymbol{a}_t, \varepsilon \right) &= \left[1 - \chi\left(\varepsilon^*_t, \varepsilon \right) \right] \left(a^m_t + p_t a^s_t \right) \\
\overline{a}^s_t \left(\boldsymbol{a}_t, \varepsilon \right) &= \chi\left(\varepsilon^*_t, \varepsilon \right) (1/p_t) \left(a^m_t + p_t a^s_t \right) \\
\hat{\boldsymbol{a}}_t \left(\boldsymbol{a}_t \right) &= \overline{\boldsymbol{a}}_t \left(\boldsymbol{a}_t, 0 \right).
\end{aligned}$$

(ii) Interdealer market clearing

$$\left\{ \alpha \left[1 - G\left(\varepsilon^* \right) \right] A^m_{It} + \chi\left(\varepsilon^*_t, 0 \right) A^m_{Dt} \right\} \frac{1}{p_t} = \alpha G\left(\varepsilon^* \right) A^s_{It} + \left[1 - \chi\left(\varepsilon^*_t, 0 \right) \right] A^s_{Dt},$$

where $A^m_{jt} \equiv \int a^m_t dF_{jt} \left(\boldsymbol{a}_t \right)$ and $A^s_{jt} \equiv \int a^s_t dF_{jt} \left(\boldsymbol{a}_t \right)$ for $j \in \{D, I\}$.

(iii) Optimal end-of-period portfolios:

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

with

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

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 (10). Then $\hat{\mu} < \bar{\mu}$.*

Proof of Lemma 4. Define $\Upsilon(\zeta):\mathbb{R}\to\mathbb{R}$ by $\Upsilon(\zeta)\equiv\bar{\beta}\left[1+\alpha\theta(1-\bar{\beta}\delta)\zeta\right]$. Let $\hat{\zeta}\equiv\frac{(1-\alpha\theta)(\hat{\varepsilon}-\bar{\varepsilon})}{\alpha\theta\hat{\varepsilon}}$ 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 (11) and the fact that $\bar{\varepsilon}\equiv\int_{\varepsilon_L}^{\varepsilon_H}\varepsilon dG(\varepsilon)=\varepsilon_H-\int_{\varepsilon_L}^{\varepsilon_H}G(\varepsilon)\,d\varepsilon$,

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

so clearly,

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

Hence, $\hat{\mu}<\bar{\mu}$. ■

Proof of Proposition 2. 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

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

In a stationary 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 stationary equilibrium, the Euler equations (32)-(35) become

$$\mu\geq\bar{\beta},\text{ “ = ” if }\tilde{a}_{dt+1}^m>0\tag{39}$$

$$\phi^s\geq\bar{\beta}\delta\bar{\phi}^s,\text{ “ = ” if }\tilde{a}_{dt+1}^s>0\tag{40}$$

$$1\geq\frac{\bar{\beta}}{\mu}\left[1+\frac{\alpha\theta}{\varepsilon^*+\phi^s}\int_{\varepsilon^*}^{\varepsilon_H}(\varepsilon-\varepsilon^*)\,dG(\varepsilon)\right],\text{ “ = ” if }\tilde{a}_{it+1}^m>0\tag{41}$$

$$\phi^s\geq\frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon}+\alpha\theta\int_{\varepsilon_L}^{\varepsilon^*}(\varepsilon^*-\varepsilon)\,dG(\varepsilon)\right],\text{ “ = ” if }\tilde{a}_{it+1}^s>0.\tag{42}$$

(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 $\bar{\beta}<\mu$, (39) implies $\tilde{a}_{dt+1}^m=Z_D=0$, so (41) 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 (40) and (42). The interdealer market-clearing condition, $\bar{A}^s_{Dt} + \bar{A}^s_{It} = A^s_{Dt} + \alpha A^s_{It}$, must hold for all three configurations. Lemma 3 shows that this condition is equivalent to (38) and in a stationary equilibrium (38) reduces to

$$Z = \frac{\varepsilon^* + \phi^s}{\alpha\left[1 - G\left(\varepsilon^*\right)\right]}\left\{\alpha G\left(\varepsilon^*\right) A^s_I + \left[1 - \chi\left(\varepsilon^*, 0\right)\right] A^s_D\right\}.$$

This condition in turn reduces to (17) if, as shown below, the equilibrium has $0 < \varepsilon^*$. The rest of the proof proceeds in three steps.

Step 1: Try to construct a stationary monetary equilibrium with $\tilde{a}^s_{dt+1} = 0$ for all $d \in \mathcal{D}$ and $\tilde{a}^s_{it+1} > 0$ for some $i \in \mathcal{I}$. The equilibrium conditions for this case are (17) together with

$$\phi^s > \bar{\beta}\delta\bar{\phi}^s \tag{43}$$

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

$$\phi^s = \frac{\bar{\beta}\delta}{1 - \bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta\int_{\varepsilon_L}^{\varepsilon^*}\left(\varepsilon^* - \varepsilon\right)dG(\varepsilon)\right] \tag{45}$$

and

$$\tilde{a}^m_{dt+1} = 0 \text{ for all } d \in \mathcal{D} \tag{46}$$

$$\tilde{a}^m_{it+1} \geq 0, \text{ with " > " for some } i \in \mathcal{I} \tag{47}$$

$$\tilde{a}^s_{dt+1} = 0 \text{ for all } d \in \mathcal{D} \tag{48}$$

$$\tilde{a}^s_{it+1} \geq 0, \text{ with " > " for some } i \in \mathcal{I}. \tag{49}$$

Conditions (44) and (45) are to be solved for the two unknowns ε^* and ϕ^s. Substitute (45) into (44) to obtain

$$1 = \frac{\bar{\beta}}{\mu}\left[1 + \alpha\theta\frac{\int_{\varepsilon^*}^{\varepsilon_H}\left(\varepsilon - \varepsilon^*\right)dG(\varepsilon)}{\varepsilon^* + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta\int_{\varepsilon_L}^{\varepsilon^*}\left(\varepsilon^* - \varepsilon\right)dG(\varepsilon)\right]}\right], \tag{50}$$

which is a single equation in ε^*. Define

$$T\left(x\right) \equiv \frac{\int_{x}^{\varepsilon_H}\left(\varepsilon - x\right)dG(\varepsilon)}{\frac{1}{1-\bar{\beta}\delta}x + \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\hat{T}\left(x\right)} - \frac{\mu - \bar{\beta}}{\bar{\beta}\alpha\theta} \tag{51}$$

with

$$\hat{T}\left(x\right) \equiv \bar{\varepsilon} - x + \alpha\theta\int_{\varepsilon_L}^{x}\left(x - \varepsilon\right)dG(\varepsilon), \tag{52}$$

and notice that ε^* solves (50) 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 (10)), 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 (45). Given ε^* and ϕ^s, the values of Z, $\bar{\phi}^s$, ϕ_t^m, and p_t are obtained using (17) (with $A_I^s = A^s$ and $A_D^s = 0$), (14), (15), and (16). To conclude this step, notice that for this case to be an equilibrium, (43) must hold, or equivalently, using $\bar{\phi}^s = \varepsilon^* + \phi^s$ and (45), it must be that $\hat{T}(\varepsilon^*) > 0$, where $\hat{T}$ is the continuous function on $[\varepsilon_L, \varepsilon_H]$ defined in (52). 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 (51), we know that $\varepsilon^* < \hat{\varepsilon}$ if and only if $T(\hat{\varepsilon}) < 0 = T(\varepsilon^*)$, i.e., if and only if

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

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 (10). 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 stationary 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 (17), (44), (46), and (47), together with

$$\phi^s = \bar{\beta}\delta\bar{\phi}^s \tag{53}$$
$$\phi^s > \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\left[\bar{\varepsilon} + \alpha\theta\int_{\varepsilon_L}^{\varepsilon^*}(\varepsilon^* - \varepsilon)\,dG(\varepsilon)\right], \text{ " = " if } \tilde{a}_{it+1}^s > 0. \tag{54}$$

$$\tilde{a}^s_{dt+1} \geq 0, \text{ with " > " for some } d \in \mathcal{D} \tag{55}$$

$$\tilde{a}^s_{it+1} = 0, \text{ for all } i \in \mathcal{I}. \tag{56}$$

The conditions (44) and (53) are to be solved for ε^* and ϕ^s. First use $\bar{\phi}^s = \varepsilon^* + \phi^s$ in (53) to obtain

$$\phi^s = \frac{\bar{\beta}\delta}{1-\bar{\beta}\delta}\varepsilon^*. \tag{57}$$

Substitute (57) in (44) to obtain

$$1 = \frac{\bar{\beta}}{\mu}\left[1 + \frac{\alpha\theta\left(1-\bar{\beta}\delta\right)\int_{\varepsilon^*}^{\varepsilon_H}\left(\varepsilon-\varepsilon^*\right)dG(\varepsilon)}{\varepsilon^*}\right], \tag{58}$$

which is a single equation in ε^*. Define

$$R\left(x\right) \equiv \frac{\left(1-\bar{\beta}\delta\right)\int_{x}^{\varepsilon_H}\left(\varepsilon-x\right)dG(\varepsilon)}{x} - \frac{\mu-\bar{\beta}}{\bar{\beta}\alpha\theta} \tag{59}$$

and notice that ε^* solves (58) if and only if it satisfies $R\left(\varepsilon^*\right) = 0$. R is a continuous real-valued function on $[\varepsilon_L, \varepsilon_H]$, with

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

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

and

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

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

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

then there exists a unique $\varepsilon^* \in (\varepsilon_L, \varepsilon_H)$ that satisfies $R\left(\varepsilon^*\right) = 0$ (and $\varepsilon^* \downarrow \varepsilon_L$ as $\mu \uparrow \mu^o$). Having solved for ε^*, ϕ^s is obtained from (57). Given ε^* and ϕ^s, the values of Z, $\bar{\phi}^s$, ϕ^m_t, and p_t are obtained using (17) (with $A^s_D = A^s - A^s_I = \delta A^s$), (14), (15), and (16). Notice that for this case to be an equilibrium (54) must hold, or equivalently, using (57), it must be that $\hat{T}\left(\varepsilon^*\right) < 0$, which in turn is equivalent to $\hat{\varepsilon} < \varepsilon^*$. With (59), we know that $\hat{\varepsilon} < \varepsilon^*$ if and only if $R\left(\varepsilon^*\right) = 0 < R\left(\hat{\varepsilon}\right)$, i.e., if and only if

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

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 stationary 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 stationary 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 stationary monetary equilibrium with $\tilde{a}^s_{dt+1} > 0$ for some $d \in \mathcal{D}$ and $\tilde{a}^s_{it+1} > 0$ for some $i \in \mathcal{I}$. The equilibrium conditions are (17), (44), (45), (46), (47), and (53) with

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

Notice that ε^* and ϕ^s are obtained as in Step 2. Now, however, (45) must also hold, which together with (57) 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 (17) is used to obtain Z, while (14), (15), and (16) imply $\bar{\phi}^s$, ϕ^m_t, 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 (45) and (51), and part $(v)(b)$ from (57) and (59). ■

Corollary 3 *The marginal valuation, ε^*, characterized in Proposition 2 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 of Corollary 3. For $\mu \in \left(\bar{\beta}, \hat{\mu}\right)$, implicitly differentiate $R(\varepsilon^*) = 0$ (with R given by (59)), and for $\mu \in (\hat{\mu}, \bar{\mu})$, implicitly differentiate $T(\varepsilon^*) = 0$ (with T given by (51)) to obtain

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

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

Proof of Proposition 3. Recall that $\partial \varepsilon^* / \partial \mu < 0$ (Corollary 3). (i) From (13),

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

and from (19), $\partial\phi^s/\partial\iota = \bar{\beta}\partial\phi^s/\partial\mu < 0$. (ii) Condition (14) implies $\partial\bar{\phi}^s/\partial\mu = \partial\varepsilon^*/\partial\mu + \partial\phi^s/\partial\mu < 0$. (iii) From (17) it is clear that $\partial Z/\partial\varepsilon^* > 0$, so $\partial Z/\partial\mu = (\partial Z/\partial\varepsilon^*)(\partial\varepsilon^*/\partial\mu) < 0$. From (15), $\partial\phi_t^m/\partial\mu = (y_t/A_t^m)\,\partial Z/\partial\mu < 0$. ■

Proof of Proposition 4. From condition (18),

$$\frac{\partial\varepsilon^*}{\partial(\alpha\theta)} = \frac{\frac{\mu-\bar{\beta}}{\alpha\theta}\left[\varepsilon^* + \bar{\beta}\delta\left(\bar{\varepsilon}-\varepsilon^*\right)\mathbb{I}_{\{\hat{\mu}<\mu\}}\right]}{\bar{\beta}\alpha\theta(1-\bar{\beta}\delta)\left[1-G\left(\varepsilon^*\right)\right] + (\mu-\bar{\beta})\left\{1+\bar{\beta}\delta\left[\alpha\theta G\left(\varepsilon^*\right)-1\right]\mathbb{I}_{\{\hat{\mu}<\mu\}}\right\}} > 0. \tag{60}$$

(i) From (13),

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

(ii) From (14), $\partial\bar{\phi}^s/\partial(\alpha\theta) = \partial\varepsilon^*/\partial(\alpha\theta) + \partial\phi^s/\partial(\alpha\theta) > 0$. (iii) For $\mu \in (\hat{\mu},\bar{\mu})$, (17) implies $\partial Z/\partial\alpha = (\partial Z/\partial\varepsilon^*)(\partial\varepsilon^*/\partial\alpha) > 0$ and therefore $\partial\phi_t^m/\partial\alpha = (\partial Z/\partial\alpha)(y_t/A_t^m) > 0$. ■

Proof of Proposition 5. (i) The result is immediate from the expression for A_D^s in Proposition 2. (ii) From (10) and (11),

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

Notice that $\partial\hat{\mu}/\partial(\alpha\theta)$ approaches a positive value as $\alpha\theta \to 0$ and a negative value as $\alpha\theta \to 1$. Also, $\hat{\mu} \to \bar{\beta}$ both when $\alpha\theta \to 0$ and when $\alpha\theta \to 1$. Hence, $\mu > \bar{\beta} = \lim_{\alpha\theta\to 0}\hat{\mu} = \lim_{\alpha\theta\to 1}\hat{\mu}$ 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 $A_D^s > 0$. ■

Proof of Proposition 6. (i) Differentiate (20) 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. Also, from (19), $\partial\mathcal{V}/\partial\iota = \bar{\beta}\partial\mathcal{V}/\partial\mu < 0$. (ii) From (20),

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

and both are positive since $\partial\varepsilon^*/\partial(\alpha\theta) > 0$ (see (60)). ■

Proof of Proposition 7. (i) For $\bar{\beta} < \mu \leq \hat{\mu}$, $\partial\mathcal{P}/\partial\mu = \left[\bar{\beta}\delta/(1-\bar{\beta}\delta)\right](\partial\varepsilon^*/\partial\mu) < 0$, and for $\hat{\mu} < \mu < \bar{\mu}$, $\partial\mathcal{P}/\partial\mu = \left[\bar{\beta}\delta/(1-\bar{\beta}\delta)\right]\alpha\theta G(\varepsilon^*)(\partial\varepsilon^*/\partial\mu) < 0$. In both cases, $\partial\mathcal{P}/\partial\iota = \bar{\beta}\partial\mathcal{P}/\partial\mu < 0$. (ii) For $\bar{\beta} < \mu \leq \hat{\mu}$, $\partial\mathcal{P}/\partial(\alpha\theta) = \left[\bar{\beta}\delta/(1-\bar{\beta}\delta)\right](\partial\varepsilon^*/\partial(\alpha\theta)) > 0$, and for $\hat{\mu} < \mu < \bar{\mu}$, $\partial\mathcal{P}/\partial\mu = \left[\bar{\beta}\delta/(1-\bar{\beta}\delta)\right]\{\alpha\theta G(\varepsilon^*)[\partial\varepsilon^*/\partial(\alpha\theta)] + \int_{\varepsilon_L}^{\varepsilon^*} G(\varepsilon)\,d\varepsilon\} > 0$. ■

Proposition 8 *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 stationary monetary equilibrium, $\partial\phi^s/\partial\sigma > 0$ and $\partial\bar{\phi}^s/\partial\sigma > 0$.*

Proof of Proposition 8. From the definition of the mean-preserving spread, for any $\Delta > 0$,

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

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

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

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 (18) is

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

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

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

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

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

implies $-\left[\delta-\left(1-\bar{\beta}\delta\right)/\left(\mu-\bar{\beta}\right)\right]=(1-\delta\mu)/\left(\mu-\bar{\beta}\right)>0$. Given that $\partial\varepsilon^*/\partial\sigma>0$ for all $\mu\in\left(\bar{\beta},\bar{\mu}\right)$, (13) and (14) 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 9 *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*

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

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

Proof of Proposition 9. In Economy A the marginal investor valuation, ε^*, is characterized by (18), while in Economy B the marginal investor valuation is the $\tilde{\varepsilon}^*$ that solves

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

Define

$$\tilde{G}\left(\varepsilon\right)=\begin{cases}0 & \text{for } \varepsilon\leq\tilde{\varepsilon}_L\\ \frac{\alpha}{\tilde{\alpha}}G\left(\varepsilon-c\right)+\left(1-\frac{\alpha}{\tilde{\alpha}}\right)\mathbb{I}_{\{\varepsilon^*<\varepsilon-c\}} & \text{for } \tilde{\varepsilon}_L\leq\varepsilon\leq\tilde{\varepsilon}_H\\ 1 & \text{for } \tilde{\varepsilon}_H<\varepsilon\end{cases}\tag{61}$$

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

$$c\equiv\frac{\bar{\beta}\delta\mathbb{I}_{\{\hat{\mu}<\mu\}}}{1-\bar{\beta}\delta\left(1-\mathbb{I}_{\{\hat{\mu}<\mu\}}\right)}\left(1-\frac{\alpha}{\tilde{\alpha}}\right)\left(\bar{\varepsilon}-\varepsilon^*\right).\tag{62}$$

With (61) and (62), the equilibrium mapping for Economy B becomes

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

If we replace $\tilde{\varepsilon}^*=\varepsilon^*+c$ in this last expression, it reduces to (18), a condition that holds because ε^* is the equilibrium marginal valuation for Economy A. Hence, $\tilde{\varepsilon}^*=\varepsilon^*+c$ with c given by (62) is the equilibrium marginal valuation for Economy B. Notice that $\tilde{\alpha}\tilde{G}\left(\tilde{\varepsilon}^*\right)=\tilde{\alpha}\tilde{G}\left(\varepsilon^*+c\right)=\alpha G\left(\varepsilon^*\right)$, so (20) implies that trade volume in Economy B is the same as in Economy A. ■

B Supplementary material: data, estimation, and simulation

B.1 Heteroskedasticity-based estimator

In this section we explain the H-based estimator used in Section 6.2. 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

$$\Delta i_t = \kappa Y_t + \varpi x_t + \epsilon_t \tag{63}$$

$$Y_t = \rho \Delta i_t + x_t + \eta_t, \tag{64}$$

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 (63) represents the monetary policy reaction to asset returns and possibly other variables represented by x_t. Equation (64) 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 (63) and (64) were the true model and one were to run an OLS regression on an equation like (21), 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 (63) and (64) can be solved for $\Delta i_t = \frac{1}{1-\rho\kappa}\left[\epsilon_t + \kappa\eta_t + (\kappa + \varpi)\, x_t\right]$ and $Y_t = \frac{1}{1-\rho\kappa}\left[\rho\epsilon_t + \eta_t + (1+\rho\varpi)\, x_t\right]$. 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 3.53 basis points (bps) in subsample S_0 and 6.84 bps in subsample S_1. The standard deviation of $\mathcal{R}_t^I$ is 49.67 bps in subsample S_0 and 64.22 bps in subsample S_1. The correlation between Δi_t and $\mathcal{R}_t^I$ is 0.19 in subsample S_0 and -0.4 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 (21), 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.[34] By

[34] 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.[35] We then estimate b in (21) 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 (21) setting $\Delta i_t = \hat{z}_t$.

The sample period is again 1994-2001, but the data from Gorodnichenko and Weber (2016) that we use contain intraday high-frequency interest rates for 64 policy announcement days (we used data for 73 announcement days in the analysis of Section 6.2). The columns labeled "HFIV" in Table 1 report the HFIV estimates. The stock return is expressed in percentage terms. The first row reports estimates of the reaction of equity returns to monetary policy shocks. The point estimate for b in (21) is -8.57. This means that a 1 bp increase in the policy rate causes a reduction of 8.57 bps in the stock market return on the day of the policy announcement. The estimated effects of monetary policy announcements on the turnover rate are reported in the second row. A 1 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 $-.000043$. The daily marketwide turnover rate for the sample period is .0037 (i.e., on average, stocks turn over .94 times during a typical year composed of 252 trading days), which means that an increase in the policy rate of 1 bp causes a reduction in the marketwide turnover rate on the day of the policy announcement of about 1.16 percent of its typical level.

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contracts settle on the effective federal funds rate *averaged over the month covered by the contract.* See Section B.4.4 for details.

[35] We 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. Their data are available at http://faculty.chicagobooth.edu/michael.weber/research/data/replication_dataset_gw.xlsx.

For each of the 20 portfolios analyzed in Section 6.3, the two columns in Table 4 labeled "HFIV" report the HFIV estimates of the responses (on the day of the policy announcement) of the return and turnover of the portfolio to a 1 pp increase in the policy rate.

All the estimates in the column labeled "Return" are negative (all but one are significant at the 1 percent level) as predicted by the theory. Also as predicted by the quantitative theory, the magnitude of the estimates tends to increase with the turnover liquidity of the portfolio. The HFIV estimates for the response of the turnover rates are all negative and for the most part statistically significant at the 1% level, as predicted by the theory. Also as predicted by the theory, the magnitude of the estimates tends to increase with the turnover liquidity of the portfolio.

B.3 More on disaggregative announcement-day effects

In Section 6.3 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.

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

$$\mathcal{R}_t^s = \alpha^s + \beta_0^s \mathcal{T}_t^I + \sum_{j=1}^{K} \beta_j^s f_{j,t} + \varepsilon_t^s, \tag{65}$$

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.[36] Let t_k denote the day of the k^{th} policy announcement (we use 73 policy announcement days from our sample period 1994-2001). For each stock s, regression (65) is run 73 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 292 estimates, $\{\{\beta_j^s(k)\}_{j=0}^3\}_{k=1}^{73}$, 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 $i = 1, ..., 20$. For each portfolio $i \in \{1, ..., 20\}$ 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 (21) 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 Section 6.3.

For each of the 20 portfolios, Table 5 reports the E-based estimates of the responses (on the day of the policy announcement) of the return and turnover 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.

[36] In 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 $SMB_t = (1/3)\left(\mathcal{R}_t^{SG} + \mathcal{R}_t^{SN} + \mathcal{R}_t^{SV}\right) - (1/3)\left(\mathcal{R}_t^{BG} + \mathcal{R}_t^{BN} + \mathcal{R}_t^{BV}\right)$ and $HML_t = (1/2)\left(\mathcal{R}_t^{SV} + \mathcal{R}_t^{BV}\right) - (1/2)\left(\mathcal{R}_t^{SG} + \mathcal{R}_t^{BG}\right)$, 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).

Notice that by sorting portfolios on the β_0's estimated from (65), 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 1994-2001, $\{(\mathcal{R}_t^i)_{i=1}^{20}\}$, and run (65) 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 8.[37] 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 5 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 (21) with $Y_t^I = \mathcal{R}_t^I$). Then according to the basic CAPM model, the effect on portfolio $i \in \{1, ..., 20\}$ 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 8). Figure 9 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 5.

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),

$$KY_t = \sum_{j=1}^{J} C_j Y_{t-j} + \varepsilon_t, \tag{66}$$

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, (66) can be represented by the reduced-form VAR

$$Y_t = \sum_{j=1}^{J} B_j Y_{t-j} + u_t, \tag{67}$$

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

$$u_t = K^{-1} \varepsilon_t \tag{68}$$

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

is an error term with

$$\Xi \equiv \mathbb{E}\left(u_t u_t'\right) = K^{-1}K^{-1\prime}. \tag{69}$$

The reduced-form VAR (67) 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 (68), we know that the disturbances of the reduced-form VAR (67) are linear combinations of the structural shocks, ε_t, so in order to use (67) 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, (69) only provides $n(n+1)/2$ independent equations involving the elements of K^{-1}, so $n\left(n-1\right)/2$ additional independent conditions would be necessary to find all elements of K^{-1}. This is the well-known identification problem of the SVAR (66). 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.[38]

The VAR we estimate consists of three variables, i.e., $Y_t = \left(i_t, \mathcal{R}_t^I, \mathcal{T}_t^I\right)'$, 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 6.1 and 6.2. Denote $\varepsilon_t = \left(\varepsilon_t^i, \varepsilon_t^{\mathcal{R}}, \varepsilon_t^{\mathcal{T}}\right)'$, $u_t = \left(u_t^i, u_t^{\mathcal{R}}, u_t^{\mathcal{T}}\right)'$, 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

$$\begin{bmatrix} u_t^i \\ u_t^{\mathcal{R}} \\ u_t^{\mathcal{T}} \end{bmatrix} = \begin{bmatrix} k_i^i \\ k_{\mathcal{R}}^i \\ k_{\mathcal{T}}^i \end{bmatrix} \varepsilon_t^i + \begin{bmatrix} k_i^{\mathcal{R}} \\ k_{\mathcal{R}}^{\mathcal{R}} \\ k_{\mathcal{T}}^{\mathcal{R}} \end{bmatrix} \varepsilon_t^{\mathcal{R}} + \begin{bmatrix} k_i^{\mathcal{T}} \\ k_{\mathcal{R}}^{\mathcal{T}} \\ k_{\mathcal{T}}^{\mathcal{T}} \end{bmatrix} \varepsilon_t^{\mathcal{T}}. \tag{70}$$

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, $\left(\varepsilon_t^i, \varepsilon_t^{\mathcal{R}}, \varepsilon_t^{\mathcal{T}}\right)$, 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 $\left\{\varepsilon_t^i\right\}$. 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 (70) we have $\eta_t = k_i^{\mathcal{R}}\varepsilon_t^{\mathcal{R}} + k_i^{\mathcal{T}}\varepsilon_t^{\mathcal{T}}$, so $\mathbb{E}\left(\varepsilon_t^i \eta_t\right) = \mathbb{E}\left[\varepsilon_t^i\left(k_i^{\mathcal{R}}\varepsilon_t^{\mathcal{R}} + k_i^{\mathcal{T}}\varepsilon_t^{\mathcal{T}}\right)\right] = 0$ (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

[38] The 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.

alternative is to find a proxy (instrumental) variable for it. Suppose there is a variable z_t such that

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

Then

$$\Lambda \equiv \mathbb{E}(z_t u_t) = K^{-1}\mathbb{E}(z_t\varepsilon_t) = \left(k_i^i, k_{\mathcal{R}}^i, k_{\mathcal{T}}^i\right)' v. \tag{71}$$

Since $\Lambda = (\Lambda_1, \Lambda_2, \Lambda_3)'$ is a known (3×1) vector, we can identify the coefficients of interest, $\left(k_i^i, k_{\mathcal{R}}^i, k_{\mathcal{T}}^i\right)$ up to the sign of the scalar v. To see this, notice (71) implies

$$vk_i^i = \Lambda_1 \tag{72}$$

$$vk_{\mathcal{R}}^i = \Lambda_2 \tag{73}$$

$$vk_{\mathcal{T}}^i = \Lambda_3 \tag{74}$$

with

$$v^2 = \mathbb{E}(z_t u_t)'\Xi^{-1}\mathbb{E}(z_t u_t). \tag{75}$$

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 $\left(k_i^i, k_{\mathcal{R}}^i, k_{\mathcal{T}}^i\right)$, i.e., combining (72) with (73), and (72) with (74), yields

$$\frac{k_{\mathcal{R}}^i}{k_i^i} = \frac{\Lambda_2}{\Lambda_1} \tag{76}$$

$$\frac{k_{\mathcal{T}}^i}{k_i^i} = \frac{\Lambda_3}{\Lambda_1}. \tag{77}$$

Thus, $k_{\mathcal{R}}^i$ and $k_{\mathcal{T}}^i$ are identified. From (72), 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.[39]

[39] 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 contracts settle on the effective federal funds rate *averaged over the month covered by the contract.* See Section B.4.4 for details.

That is, we restrict our sample to $t \in S_1$ and set $\{z_t\} = \left\{i_{t,m_t^*+20} - i_{t,m_t^*-10}\right\}$, 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.[40] 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 $\hat{\kappa}^{\mathcal{T}} = \Lambda_3/\Lambda_1$, (76) and (77) 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.[41] For example, in our impulse responses we normalize the shock ε_t^i so that it induces a 1 pp increase in the level of the policy rate i_t on impact. To see this, consider (70) with $\varepsilon_t^{\mathcal{R}} = \varepsilon_t^{\mathcal{T}} = 0$. Then for any k_i^i, the shock that induces an x pp increase in the level of the policy rate on impact (e.g., at $t = 0$) is $\varepsilon_0^i = (x/100)/k_i^i = (x/100)/(\Lambda_1/v)$.

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

[40] We 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.

[41] Alternatively, (72) and (75) can be combined to get $k_i^i = \Lambda_1/v$, which is then identified up to the sign of v.

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, $\left\{Y_t^b\right\}$, 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, $\left\{z_t^b\right\}$, 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 $\left\{Y_t^b\right\}$ and $\left\{z_t^b\right\}$ 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 Lag length

The Akaike information criterion (AIC) suggests a VAR specification with 10 lags, while Schwarz's Bayesian information criterion (SBIC) and the Hannan and Quinn information criterion (HQIC) suggest a specification with 5 lags. In order to choose between these alternatives, we check which specification delivers a better estimate of the true impulse responses generated by the quantitative theory presented in Section 7. Specifically, the baseline parameters and the dividend process are calibrated as in Section 7.2. For the policy rate we adopt the AR(1) process estimated from the data (see footnote 30 in Section 7.2 for details). We then proceed as follows:

1. Compute the equilibrium functions characterized by (23)-(26) for the calibrated model.

2. Simulate 1,000 samples of the dividend and the policy rate, each sample of length equal to our data sample (1,996 days, which is the number of trading days between January 1, 1994, and December 31, 2001).[42]

3. Compute the equilibrium of the model 1,000 times (one for each realization of the simulated dividend and policy rate paths) to produce 1,000 synthetic data samples (each

[42]The policy rate is simulated using the AR(1) process we estimated for our proxy for the policy rate (see footnote 30 in Section 7.2). The initial condition for the policy rate is the mean value of the estimated AR(1) process. The initial condition for the dividend is normalized to 1.

consisting of 1,996 days) for the policy rate and the (arithmetic) average (across the 20 stock classes) of the stock return and the turnover rate.[43]

4. For each synthetic data set, estimate our baseline VAR specification with 10 lags and an alternative specification with 5 lags. For each specification, calculate the impulse responses to a 1 bp increase in the policy rate.[44]

5. Calculate the average (median) impulse responses over the 1,000 synthetic samples and calculate the 95 percent confidence intervals using the distribution of estimates over the 1,000 synthetic samples. Do this for the specification with 10 lags and for the one with 5 lags.

6. Use the equilibrium conditions of the model to compute the true theoretical impulse responses to a 1 bp increase in the policy rate that follows the estimated AR(1) process.[45]

For each variable, Figure 7 reports the average (median) impulse response and the 95 percent confidence interval corresponding to the VAR specifications with 5 and 10 lags, along with the true theoretical impulse response implied by the equilibrium conditions. The impulse responses from the VAR specification with 10 lags and those from the VAR specification with 5 lags approximate the true theoretical responses about as well.

B.4.4 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 $\left\{f_{s,t}^{0}\right\}_{t=1}^{T}$ 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.[46] Let $\{r_t\}_{t=1}^{T}$ be the (average) daily fededral funds rate calculated *at the end* of day t. Finally, for $j = 1, ..., T - t$, let $E_t r_{t+j}$ denote the expectation of the spot federal funds rate on day $t + j$

[43] Measurement noise is added to the equilibrium path of the turnover rate, as explained in footnote 32. Linear interpolation is used to compute the equilibrium variables for realizations of the policy rate that lie outside the set of states of the Markov chain that is used to compute the equilibrium functions.

[44] We use the same policy dates on the synthetic data as in the actual data. We also follow the same identification procedure used in the empirical section and described in Section B.4.1. To replicate this instrumental-variable identification procedure in the context of the model simulations, as instrument (z_t) we simply use with the change in the policy rate (which is indeed exogenous in the model).

[45] Here again, linear interpolation is used to compute the equilibrium variables for realizations of the policy rate that are not states of the Markov chain used to compute the equilibrium functions.

[46] Contracts 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.

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

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

Hence, for $t = 1, ..., T$,

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

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 $t \geq 1$.[47] Then

$$E_t r_i = r_t \text{ for } i = t, ..., T$$
$$E_{t-1} r_i = E_{t-1} r_t \text{ for } i = t+1, ...T.$$

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

$$f_{s,t}^0 - f_{s,t-1}^0 = \frac{T+1-t}{T}\left(r_t - E_{t-1} r_t\right), \tag{78}$$

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 (78) we can recover the unexpected change in the federal funds rate on the day of the FOMC announcement, t, as follows:

$$r_{t+1} - E_t r_{t+1} = \frac{T}{T-t}\left(f_{s,t+1}^0 - f_{s,t}^0\right) \text{ for } t = 0, ..., T-1. \tag{79}$$

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 $z_t = \frac{T}{T-t}\left(f_{s,t+1}^0 - f_{s,t}^0\right) \equiv i_{t,m_t^*+20} - i_{t,m_t^*-10}$, 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.

[47] If 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).

B.4.5 Portfolio-based VAR analysis

In Section 6.4 we estimated a VAR consisting of three variables, i.e., $\{i_t, \mathcal{R}_t^I, \mathcal{T}_t^I\}$, where i_t is a proxy for the policy rate (the 3-month Eurodollar futures rate), and $\mathcal{R}_t^I$, and $\mathcal{T}_t^I$ are the daily measures of the average NYSE stock return and turnover described in Sections 6.1 and 6.2. In this section we follow the same methodology described in Section 6.4, but instead estimate a separate VAR for each of the individual liquidity-based portfolios constructed as described in Section 6.3. That is, for each portfolio $i = 1, ..., 20$, we estimate a VAR consisting of three variables $\{i_t, \mathcal{R}_t^i, \mathcal{T}_t^i\}$. The results from this exercise confirm and extend the findings of Section 6.3 and Section 6.4. To illustrate, for three liquidity-based portfolios, Figure 10 reports the impulse responses of the daily portfolio return and turnover rate to a 1 bp unexpected increase in the policy rate for a forecast horizon of 30 days. As in Section 6.3, we again find that on the announcement day, the negative responses of returns and turnover 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 by the E-based and H-based estimates reported in Table 2.[48] Interestingly, Figure 10 also confirms that, as in the quantitative theory, the dynamic responses of returns and turnover for more liquid portfolios tend to be not only larger but also more persistent than for less liquid portfolios.

B.5 Extended sample: 1994-2007

We have focused our empirical analysis on the sample period 1994-2001. We chose to end the sample period in 2001 because our theory abstracts from credit, and credit conditions in the U.S. financial market appear to have eased dramatically in the six years leading up to the 2007 financial crisis.[49] In this section, we report empirical results for the longer sample period, 1994-2007. The basic results on the announcement-day effects of monetary policy surprises on returns and turnover are reported in Table 6 (this table is the analogue of Table 4).

[48] Aside from the fact that the VAR specification is more flexible than (21), our VAR estimation also relies on the HFIV identification scheme. In fact, notice that even for the simple specification (21), Table 4 and Table 6 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.

[49] For example, the private-label securitization market grew in issuance from under \$500 billion to over \$2 trillion in 2006, the year before the crisis, see e.g., Gorton and Metrick (2012).

C Supplementary material: Theory

C.1 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 (18) implies*

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

with

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

Given ε^*, the closed-form expressions for the equilibrium allocation are given in Proposition 2.

Example 2 *Suppose that the probability distribution over investor valuations is distributed uniformly on $[0,1]$. Then (18) implies*

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

with

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

and where $\bar{\iota} \equiv \left(\bar{\mu}-\bar{\beta}\right)/\bar{\beta}$ and $\hat{\varepsilon} = (1-\sqrt{1-\alpha\theta})/\left(\alpha\theta\right)$. Given ε^*, the closed-form expressions for the equilibrium allocation are given in Proposition 2.

C.2 Equilibrium conditions for the general model

In this section we derive the equilibrium conditions for the general model, reported in Section 7. 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

$\boldsymbol{x}_t = (A_t^m, y_t, \mu_t) \in \mathbb{R}_+^3$. Asset prices in a recursive equilibrium will be $\phi_t^s = \phi^s(\boldsymbol{x}_t)$, $\bar{\phi}_t^s = \bar{\phi}^s(\boldsymbol{x}_t)$, $\phi_t^m = \phi^m(\boldsymbol{x}_t)$, $p_t^s = p^s(\boldsymbol{x}_t)$, and $\varepsilon_t^{s*} = \varepsilon^{s*}(\boldsymbol{x}_t)$. Let A_t^{ms} denote the amount of money that investors have available to trade asset s at the beginning of period t. The laws of motion for the state variables A_t^m, y_t, and μ_t are exogenous (as described above) while $A_t^{ms} = \Psi^s(\boldsymbol{x}_t)$, where the decision rule Ψ^s is determined in equilibrium.

The investor's value functions are

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

with

$$\begin{aligned}
\bar{W}^I(\boldsymbol{x}_t) \equiv T(\boldsymbol{x}_t) + &\max_{(\tilde{a}_{t+1}^m, (\tilde{a}_{t+1}^s)_{s\in\mathbb{N}})\in\mathbb{R}_+^{N+1}} \Big\{ -\phi^m(\boldsymbol{x}_t)\,\tilde{a}_{t+1}^m - \sum_{s\in\mathbb{N}} \phi^s(\boldsymbol{x}_t)\,\tilde{a}_{t+1}^s \\
&+ \beta\mathbb{E}\left[\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1}) \middle| \boldsymbol{x}_t\right] \Big\}, \\
\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1}) = &\max_{(a_{t+1}^{ms})_{s\in\mathbb{N}}\in\mathbb{R}_+^N} \int V^I((a_{t+1}^{ms}, a_{t+1}^s)_{s\in\mathbb{N}}, \varepsilon; \boldsymbol{x}_{t+1})\, dG(\varepsilon) \qquad (80) \\
&\text{s.t.} \sum_{s\in\mathbb{N}} a_{t+1}^{ms} \leq \tilde{a}_{t+1}^m,
\end{aligned}$$

and

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

where $T(\boldsymbol{x}_t) \equiv (\mu_t - 1)\,\phi^m(\boldsymbol{x}_t)\, A_t^m$, 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 the optimal partition of money across asset classes chosen by an investor at the beginning of the period.

Lemma 5 *The $(a_{t+1}^{ms})_{s\in\mathbb{N}}$ that solves (80) satisfies*

$$\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \geq \phi^m(\boldsymbol{x}_{t+1}) + \alpha^s\theta \int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^s(\boldsymbol{x}_{t+1})} y_{t+1}\, dG(\varepsilon), \qquad (81)$$

with "=" if $a_{t+1}^{ms} > 0$.

Proof. The objective function on the right side of (80) can be written as

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

The Lagrangian for the maximization in (80) is

$$\begin{aligned}\mathcal{L}\left((a^{ms}_{t+1})_{s\in\mathbb{N}}; \tilde{a}^{m}_{t+1}, \boldsymbol{x}_{t+1}\right) = & \sum_{s\in\mathbb{N}} \left[\phi^{m}(\boldsymbol{x}_{t+1}) + \alpha^{s}\theta \int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^{s}(\boldsymbol{x}_{t+1})} y_{t+1} dG(\varepsilon) \right] a^{ms}_{t+1} \\ & + \sum_{s\in\mathbb{N}} \zeta^{ms}(\boldsymbol{x}_{t+1}) a^{ms}_{t+1} + \xi(\boldsymbol{x}_{t+1}) \left(\tilde{a}^{m}_{t+1} - \sum_{s\in\mathbb{N}} a^{ms}_{t+1} \right),\end{aligned} \tag{82}$$

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

$$\phi^{m}(\boldsymbol{x}_{t+1}) + \alpha^{s}\theta \int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^{s}(\boldsymbol{x}_{t+1})} y_{t+1} dG(\varepsilon) + \zeta^{ms}(\boldsymbol{x}_{t+1}) - \xi(\boldsymbol{x}_{t+1}) = 0,$$

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

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

Lemma 6 *The portfolio $(\tilde{a}^{m}_{t+1}, (\tilde{a}^{s}_{t+1})_{s\in\mathbb{N}})$ chosen by an investor in the second subperiod of period t with state $\boldsymbol{x}_t$ of a recursive equilibrium, satisfies*

$$\phi^{s}(\boldsymbol{x}_t) \geq \beta\delta\mathbb{E}\left[\bar{\varepsilon} y_{t+1} + \phi^{s}(\boldsymbol{x}_{t+1}) + \alpha^{s}\theta \int_{\varepsilon_L}^{\varepsilon^{s*}(\boldsymbol{x}_{t+1})} [\varepsilon^{s*}(\boldsymbol{x}_{t+1}) - \varepsilon] y_{t+1} dG(\varepsilon) \middle| \boldsymbol{x}_t \right] \tag{83}$$

$$\phi^{m}(\boldsymbol{x}_t) \geq \beta\mathbb{E}\left[\phi^{m}(\boldsymbol{x}_{t+1}) + \alpha^{s}\theta \int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^{s}(\boldsymbol{x}_{t+1})} y_{t+1} dG(\varepsilon) \middle| \boldsymbol{x}_t \right], \tag{84}$$

where (83) holds with "=" if $\tilde{a}^{s}_{t+1} > 0$ and (84) holds with "=" if $a^{ms}_{t+1} > 0$.

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

$$\max_{(\tilde{a}^{m}_{t+1}, (\tilde{a}^{s}_{t+1})_{s\in\mathbb{N}}) \in \mathbb{R}^{N+1}_{+}} \left\{ -\phi^{m}(\boldsymbol{x}_t)\tilde{a}^{m}_{t+1} - \sum_{s\in\mathbb{N}} \phi^{s}(\boldsymbol{x}_t)\tilde{a}^{s}_{t+1} + \beta\mathbb{E}\left[\bar{V}^{I}(\tilde{a}^{m}_{t+1}, (a^{s}_{t+1})_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1}) \middle| \boldsymbol{x}_t \right] \right\},$$

with

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

where $\mathcal{L}\left((a^{ms}_{t+1})_{s\in\mathbb{N}};\tilde{a}^m_{t+1},\boldsymbol{x}_{t+1}\right)$ is defined in the proof of Lemma 5. We then have,

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

The first-order conditions for the investor's maximization problem in the second subperiod are

$$
\begin{aligned}
&-\phi^s(\boldsymbol{x}_t)+\beta\mathbb{E}\left[\left.\frac{\partial\bar{V}^I(\tilde{a}^m_{t+1},(a^s_{t+1})_{s\in\mathbb{N}};\boldsymbol{x}_{t+1})}{\partial\tilde{a}^s_{t+1}}\right|\boldsymbol{x}_t\right]\le 0,\text{ with “ = ” if }\tilde{a}^s_{t+1}>0\\
&-\phi^m(\boldsymbol{x}_t)+\beta\mathbb{E}\left[\left.\frac{\partial\bar{V}^I(\tilde{a}^m_{t+1},(a^s_{t+1})_{s\in\mathbb{N}};\boldsymbol{x}_{t+1})}{\partial\tilde{a}^m_{t+1}}\right|\boldsymbol{x}_t\right]\le 0,\text{ with “ = ” if }\tilde{a}^m_{t+1}>0,
\end{aligned}
$$

or equivalently,

$$
\begin{aligned}
&\phi^s(\boldsymbol{x}_t)\ge\beta\delta\mathbb{E}\left[\bar{\varepsilon}y_{t+1}+\phi^s(\boldsymbol{x}_{t+1})+\alpha^s\theta\int_{\varepsilon_L}^{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}\left[\varepsilon^{s*}(\boldsymbol{x}_{t+1})-\varepsilon\right]y_{t+1}dG(\varepsilon)\right|\left.\boldsymbol{x}_t\right]\\
&\phi^m(\boldsymbol{x}_t)\ge\beta\mathbb{E}\left[\xi(\boldsymbol{x}_{t+1})|\,\boldsymbol{x}_t\right],
\end{aligned}
$$

where the first condition holds with “=” if $\tilde{a}^s_{t+1}>0$ and the second condition holds with “=” if $\tilde{a}^m_{t+1}>0$. By Lemma 5, the second condition can be written as

$$
\phi^m(\boldsymbol{x}_t)\ge\beta\mathbb{E}\left[\phi^m(\boldsymbol{x}_{t+1})+\alpha^s\theta\int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H}\frac{\varepsilon-\varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^s(\boldsymbol{x}_{t+1})}y_{t+1}dG(\varepsilon)\right|\left.\boldsymbol{x}_t\right]
$$

with “=” if $a^{ms}_{t+1}>0$. ■

Definition 2 *A recursive equilibrium for the multiple asset economy (in which only investors can hold equity overnight) is a collection of functions,* $\{\phi^m(\cdot),\{\phi^s(\cdot),p^s(\cdot),\varepsilon^{s*}(\cdot),\Psi^s(\cdot)\}_{s\in\mathbb{N}}\}$, *that satisfy*

$$
\begin{aligned}
\phi^s\left(\boldsymbol{x}_t\right) &= \beta\delta\mathbb{E}\left[\bar{\varepsilon}y_{t+1} + \phi^s\left(\boldsymbol{x}_{t+1}\right) + \alpha^s\theta\int_{\varepsilon_L}^{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}\left[\varepsilon^{s*}\left(\boldsymbol{x}_{t+1}\right) - \varepsilon\right]y_{t+1}dG(\varepsilon)\right|\boldsymbol{x}_t\bigg] \\
\phi^m\left(\boldsymbol{x}_t\right) &\geq \beta\mathbb{E}\left[\phi^m\left(\boldsymbol{x}_{t+1}\right) + \alpha^s\theta\int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H}\frac{\varepsilon - \varepsilon^{s*}\left(\boldsymbol{x}_{t+1}\right)}{p^s\left(\boldsymbol{x}_{t+1}\right)}y_{t+1}dG(\varepsilon)\right|\boldsymbol{x}_t\bigg],\ \textit{with ``= '' if } A_{t+1}^{ms} > 0 \\
p^s\left(\boldsymbol{x}_t\right) &= \frac{\left[1 - G\left(\varepsilon^{s*}\left(\boldsymbol{x}_t\right)\right)\right]A_t^{ms}}{G\left(\varepsilon^{s*}\left(\boldsymbol{x}_t\right)\right)A^s} \\
\varepsilon^{s*}\left(\boldsymbol{x}_t\right) &= \frac{p^s\left(\boldsymbol{x}_t\right)\phi^m\left(\boldsymbol{x}_t\right) - \phi^s\left(\boldsymbol{x}_t\right)}{y_t} \\
A_t^m &= \sum_{s\in\mathbb{N}}A_t^{ms},
\end{aligned}
$$

where $A_{t+1}^{ms} = \int_{\mathcal{I}} a_{t+1}^{ms}di$.

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

$$
\begin{aligned}
\phi^s\left(\boldsymbol{x}_t\right) &= \phi_i^s y_t &(85)\\
\bar{\phi}^s\left(\boldsymbol{x}_t\right) &\equiv p^s\left(\boldsymbol{x}_t\right)\phi^m\left(\boldsymbol{x}_t\right) = \bar{\phi}_i^s y_t &(86)\\
\phi^m\left(\boldsymbol{x}_t\right)A_t^m &= Z_i y_t &(87)\\
A_t^{ms} &= \Psi^s\left(\boldsymbol{x}_t\right) = \lambda_i^s A_t^m &(88)\\
\varepsilon^{s*}\left(\boldsymbol{x}_t\right) &\equiv \frac{\bar{\phi}^s\left(\boldsymbol{x}_t\right) - \phi^s\left(\boldsymbol{x}_t\right)}{y_t} = \bar{\phi}_i^s - \phi_i^s \equiv \varepsilon_i^{s*}, &(89)
\end{aligned}
$$

the equilibrium conditions reduce to (23)-(26). Having found $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s\}_{i\in\mathbb{M},s\in\mathbb{N}}$, for a given $\boldsymbol{x}_t = \left(A_t^m, y_t, \mu_i\right)$, $\phi^s\left(\boldsymbol{x}_t\right)$ is obtained from (85), $\bar{\phi}^s\left(\boldsymbol{x}_t\right)$ from (86) (with $\bar{\phi}_i^s = \varepsilon_i^{s*} + \phi_i^s$), $\phi^m\left(\boldsymbol{x}_t\right)$ from (87), $p^s\left(\boldsymbol{x}_t\right)$ from (86), and A_t^{ms} from (88).

C.3 Open-market operations

In order to provide a more realistic description of the implementation of monetary policy, in this section we extend the model presented in Section 7 and allow the monetary authority to inject or withdraw money via open-market operations modelled as follows. In the first subperiod each investor can trade in a competitive market where the monetary authority sells B_t one-period risk-free pure-discount nominal bonds (i.e., 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 the amount of money he will have available to trade bonds in the first subperiod of t, denoted a_t^{mb}. The size of the bond issue, B_t, expressed 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. For simplicity, in this section we assume dealers do not hold equity or money overnight.

The beginning-of-period money supply in this environment 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). For example, $\tilde{\mu}_t = \mu_t / [1 + (1 - q_t)\,\omega_t]$ implies $A_{t+1}^m = \mu_t A_t^m$, so the monetary authority can implement any path $\{\mu_t\}_{t=1}^{\infty}$ of growth rates of the beginning-of-period money supply despite the random changes in the money supply induced by the open-market operations. 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 $T_t = [(\mu_t - 1) - (1 - q_t)\,\omega_t]\,\phi_t^m A_t^m$.

Let $\boldsymbol{\tau}_t \equiv (\omega_t, \mu_t)$ and assume $\{\boldsymbol{\tau}_t\}_{t=1}^{\infty}$ follows a Markov chain with transition matrix $\sigma_{ij} = \Pr(\boldsymbol{\tau}_{t+1} = \boldsymbol{\tau}_j | \boldsymbol{\tau}_t = \boldsymbol{\tau}_i)$, where $\boldsymbol{\tau}_i \equiv (\omega_i, \mu_i) \in \mathbb{R}_{++}^2$ and $\boldsymbol{\tau}_j \equiv (\omega_j, \mu_j) \in \mathbb{R}_{++}^2$ for all $i, j \in \mathbb{M} = \{1, \ldots, M\}$. The realization of $\boldsymbol{\tau}_t$ is known at the beginning of period t. 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 $\boldsymbol{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_t) \in \mathbb{R}_+^4$. Asset prices in a recursive equilibrium will be $\phi_t^s = \phi^s(\boldsymbol{x}_t)$, $\bar{\phi}_t^s = \bar{\phi}^s(\boldsymbol{x}_t)$, $\phi_t^m = \phi^m(\boldsymbol{x}_t)$, $p_t^s = p^s(\boldsymbol{x}_t)$, $q_t = q(\boldsymbol{x}_t)$, and $\varepsilon_t^{s*} = \varepsilon^{s*}(\boldsymbol{x}_t)$. 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 $A_t^{mk} = \Psi^k(\boldsymbol{x}_t)$, where the decision rule Ψ^k, for $k \in \bar{\mathbb{N}}$, is determined in equilibrium.

The investor's value functions are

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

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

$$\bar{W}^I(\boldsymbol{x}_t) \equiv T(\boldsymbol{x}_t) + \max_{(\tilde{a}_{t+1}^m, (\tilde{a}_{t+1}^s)_{s\in\mathbb{N}}) \in \mathbb{R}_+^{N+1}} \Big\{ -\phi^m(\boldsymbol{x}_t)\tilde{a}_{t+1}^m - \sum_{s\in\mathbb{N}} \phi^s(\boldsymbol{x}_t)\tilde{a}_{t+1}^s \\ + \beta\mathbb{E}\left[\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1}) \middle| \boldsymbol{x}_t\right] \Big\},$$

$$\bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1}) = \max_{(a_{t+1}^{mk})_{k\in\bar{\mathbb{N}}} \in \mathbb{R}_+^{N+1}} \int V^I(a_{t+1}^{mb}, (a_{t+1}^{ms}, a_{t+1}^s)_{s\in\mathbb{N}}, \varepsilon; \boldsymbol{x}_{t+1}) dG(\varepsilon) \tag{90}$$
$$\text{s.t. } \sum_{k\in\bar{\mathbb{N}}} a_{t+1}^{mk} \le \tilde{a}_{t+1}^m,$$

and

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

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 $\boldsymbol{x}_t$, 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 7 *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*

$$a_t^b(a_t^{mb}, q_t) = \chi(q_t, 1)\, a_t^{mb}/q_t$$
$$\bar{a}_t^{mb}(a_t^{mb}, q_t) = [1 - \chi(q_t, 1)]\, a_t^{mb},$$

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

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

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

This problem can be written as

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

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

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

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

With Lemma 7, the investor's value function in the first subperiod becomes

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

The following lemma (a generalization of Lemma 5) characterizes the optimal partition of money across asset classes chosen by an investor at the beginning of the period.

Lemma 8 *The* $(a_{t+1}^{mk})_{k\in\bar{\mathbb{N}}}$ *that solves (90) satisfies*

$$\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \geq \phi^m(\boldsymbol{x}_{t+1}) + \alpha^s \theta \int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H} \frac{\varepsilon - \varepsilon^{s*}(\boldsymbol{x}_{t+1})}{p^s(\boldsymbol{x}_{t+1})} y_{t+1} dG(\varepsilon) \quad (91)$$

$$\frac{\partial \bar{V}^I(\tilde{a}_{t+1}^m, (a_{t+1}^s)_{s\in\mathbb{N}}; \boldsymbol{x}_{t+1})}{\partial \tilde{a}_{t+1}^m} \geq \frac{\phi^m(\boldsymbol{x}_{t+1})}{q(\boldsymbol{x}_{t+1})}, \quad (92)$$

where (91) holds with "=" if $a_{t+1}^{ms} > 0$ *and (92) holds with "=" if* $a_{t+1}^{mb} > 0$.

Proof. The objective function on the right side of (90) can be written as

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

The Lagrangian for the maximization in (90) is

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

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

$$\frac{\phi^m\left(\boldsymbol{x}_{t+1}\right)}{q\left(\boldsymbol{x}_{t+1}\right)}+\zeta^{mb}\left(\boldsymbol{x}_{t+1}\right)-\xi\left(\boldsymbol{x}_{t+1}\right)=0$$

$$\phi^m\left(\boldsymbol{x}_{t+1}\right)+\alpha^s\theta\int_{\varepsilon^{s*}(\boldsymbol{x}_{t+1})}^{\varepsilon_H}\frac{\varepsilon-\varepsilon^{s*}\left(\boldsymbol{x}_{t+1}\right)}{p^s\left(\boldsymbol{x}_{t+1}\right)}y_{t+1}dG(\varepsilon)+\zeta^{ms}\left(\boldsymbol{x}_{t+1}\right)-\xi\left(\boldsymbol{x}_{t+1}\right)=0,$$

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

The following lemma (a generalization of Lemma 6) characterizes an investor's optimal portfolio choice in the second subperiod of any period with state $\boldsymbol{x}_t$.

Lemma 9 *The portfolio $(\tilde{a}^{m}_{t+1},(\tilde{a}^{s}_{t+1})_{s\in\mathbb{N}})$ chosen by an investor in the second subperiod of period t with state $\boldsymbol{x}_t$ of a recursive equilibrium, satisfies*

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

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

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

$$\max_{(\tilde{a}^m_{t+1},(\tilde{a}^s_{t+1})_{s\in\mathbb{N}})\in\mathbb{R}^{N+1}_+}\left\{-\phi^m(\boldsymbol{x}_t)\,\tilde{a}^m_{t+1}-\sum_{s\in\mathbb{N}}\phi^s(\boldsymbol{x}_t)\,\tilde{a}^s_{t+1}+\beta\mathbb{E}\left[\bar{V}^I(\tilde{a}^m_{t+1},(a^s_{t+1})_{s\in\mathbb{N}};\boldsymbol{x}_{t+1})\middle|\,\boldsymbol{x}_t\right]\right\},$$

with

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

where $\hat{\mathcal{L}}\left((a^{ms}_{t+1})_{s\in\mathbb{N}};\tilde{a}^m_{t+1},\boldsymbol{x}_{t+1}\right)$ is defined in the proof of Lemma 8. We then have,

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

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

$$\begin{aligned}-\phi^m(\boldsymbol{x}_t)+\beta\mathbb{E}\left[\frac{\partial\bar{V}^I(\tilde{a}^m_{t+1},(a^s_{t+1})_{s\in\mathbb{N}};\boldsymbol{x}_{t+1})}{\partial\tilde{a}^m_{t+1}}\middle|\,\boldsymbol{x}_t\right]&\leq 0,\text{ with " = " if }\tilde{a}^m_{t+1}>0\\-\phi^s(\boldsymbol{x}_t)+\beta\mathbb{E}\left[\frac{\partial\bar{V}^I(\tilde{a}^m_{t+1},(a^s_{t+1})_{s\in\mathbb{N}};\boldsymbol{x}_{t+1})}{\partial\tilde{a}^s_{t+1}}\middle|\,\boldsymbol{x}_t\right]&\leq 0,\text{ with " = " if }\tilde{a}^s_{t+1}>0,\end{aligned}$$

or equivalently,

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

with "=" if $\tilde{a}^s_{t+1} > 0$, for $s \in \mathbb{N}$. By Lemma 8, the first condition can be written as

$$\phi^m(\boldsymbol{x}_t)\geq\beta\mathbb{E}\left[\frac{\phi^m(\boldsymbol{x}_{t+1})}{q(\boldsymbol{x}_{t+1})}\middle|\,\boldsymbol{x}_t\right],$$

with "=" if $a_{t+1}^{mb} > 0$, or as

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

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

Definition 3 *A recursive monetary equilibrium for the multiple asset economy with open-market operations (in which only investors can hold equity overnight) is a collection of functions,* $\{\phi^m(\cdot), q(\cdot), \Psi^b(\cdot), \{\phi^s(\cdot), p^s(\cdot), \varepsilon^{s*}(\cdot), \Psi^s(\cdot)\}_{s\in\mathbb{N}}\}$*, that satisfy*

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

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

$$\phi^s(\boldsymbol{x}_t) = \phi_i^s y_t \tag{93}$$

$$\bar{\phi}^s(\boldsymbol{x}_t) = \bar{\phi}_i^s y_t \tag{94}$$

$$\phi^m(\boldsymbol{x}_t) A_t^m = Z_i y_t \tag{95}$$

$$A_t^{mk} = \Psi^k(\boldsymbol{x}_t) = \lambda_i^k A_t^m \tag{96}$$

$$\bar{\phi}^s(\boldsymbol{x}_t) \equiv p^s(\boldsymbol{x}_t)\phi^m(\boldsymbol{x}_t) \tag{97}$$

$$q(\boldsymbol{x}_t) = \min(\lambda_i^b/\omega_i, 1) \equiv q_i \tag{98}$$

$$\varepsilon^{s*}(\boldsymbol{x}_t) \equiv \frac{\bar{\phi}^s(\boldsymbol{x}_t) - \phi^s(\boldsymbol{x}_t)}{y_t} = \bar{\phi}_i^s - \phi_i^s \equiv \varepsilon_i^{s*}, \tag{99}$$

the equilibrium conditions reduce to

$$\phi_i^s = \bar{\beta}\delta \sum_{j\in\mathbb{M}} \sigma_{ij} \left[\bar{\varepsilon} + \phi_j^s + \alpha^s \theta \int_{\varepsilon_L}^{\varepsilon_j^{s*}} (\varepsilon_j^{s*} - \varepsilon) dG(\varepsilon) \right] \tag{100}$$

$$Z_i = \frac{\bar{\beta}}{\mu_i} \sum_{j\in\mathbb{M}} \sigma_{ij} \left[1 + \alpha^s \theta \int_{\varepsilon_j^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_j^{s*}}{\varepsilon_j^{s*} + \phi_j^s} dG(\varepsilon) \right] Z_j \tag{101}$$

$$\max(\omega_i/\lambda_i^b, 1) = 1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon) \tag{102}$$

$$Z_i \lambda_i^s = \frac{G(\varepsilon_i^{s*}) A^s}{1 - G(\varepsilon_i^{s*})} (\varepsilon_i^{s*} + \phi_i^s) \tag{103}$$

$$1 - \lambda_i^b = \sum_{s\in\mathbb{N}} \lambda_i^s. \tag{104}$$

This 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 $\boldsymbol{x}_t = (A_t^m, y_t, \boldsymbol{\tau}_t)$ with $\boldsymbol{\tau}_t = \boldsymbol{\tau}_i = (\omega_i, \mu_i)$, $\phi^s(\boldsymbol{x}_t)$ is obtained from (93), $\bar{\phi}^s(\boldsymbol{x}_t)$ from (94) (with $\bar{\phi}_i^s = \varepsilon_i^{s*} + \phi_i^s$), $\phi^m(\boldsymbol{x}_t)$ from (95), A_t^{mk} from (96), $p^s(\boldsymbol{x}_t)$ from (97), and $q(\boldsymbol{x}_t)$ from (98).

Notice that the economy of Section 7 corresponds to the special case of this economy with $\omega_t = 0$ for all t (which in turn implies $\lambda_i^b = 0$ for all i, so (102) is dropped from the set of equilibrium conditions). The following result shows that the benchmark nominal interest rate we used in the economy of Section 7 (obtained by pricing a hypothetical bond that is not actually traded) can be interpreted as the equilibrium nominal interest rate of an economy with explicit open-market operations.

Proposition 10 *Let $\{\phi_i^s, \varepsilon_i^{s*}, Z_i, \lambda_i^s\}_{i\in\mathbb{M}, s\in\mathbb{N}}$ be the equilibrium of the economy without bonds under monetary policy $\{\sigma_{ij}, \mu_i\}_{i,j\in\mathbb{M}}$. Let $\{\tilde{\phi}_i^s, \tilde{\varepsilon}_i^{s*}, \tilde{Z}_i, \tilde{\lambda}_i^s, \tilde{\lambda}_i^b\}_{i\in\mathbb{M}, s\in\mathbb{N}}$ be the equilibrium of the economy with open-market operations under monetary policy $\{\sigma_{ij}, \mu_i, \omega_i\}_{i,j\in\mathbb{M}}$, with*

$$\omega_i = \bar{\omega} \left[1 + \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon) \right] \text{ for some } \bar{\omega} \in (0,1).$$

Then

$$\{\tilde{\phi}_i^s, \tilde{\varepsilon}_i^{s*}, \tilde{Z}_i, \tilde{\lambda}_i^s, \tilde{\lambda}_i^b\}_{i\in\mathbb{M}} = \{\phi_i^s, \varepsilon_i^{s*}, Z_i/(1-\bar{\omega}), (1-\bar{\omega})\lambda_i^s, \bar{\omega}\}_{i\in\mathbb{M}}.$$

Moreover, the inflation rate is identical in both economies and given by

$$\Pi(\boldsymbol{x}_t, \boldsymbol{x}_{t+1}) \equiv \frac{\phi^m(\boldsymbol{x}_t)}{\phi^m(\boldsymbol{x}_{t+1})} = \frac{Z_i}{Z_j} \frac{\mu_i}{\gamma_{t+1}}.$$

The nominal interest rate in the economy with open-market operations is given by

$$\tilde{r}_i \equiv \frac{1}{q_i} - 1 = \alpha^s \theta \int_{\varepsilon_i^{s*}}^{\varepsilon_H} \frac{\varepsilon - \varepsilon_i^{s*}}{\varepsilon_i^{s*} + \phi_i^s} dG(\varepsilon),$$

and for $\sigma_{ii} \approx 1$, it is the same as the nominal interest rate in the economy with no bonds.

Proof. It is easy to verify that given $\{\sigma_{ij}, \mu_i, \omega_i\}_{i,j\in\mathbb{M}}$, the allocation $\{\tilde{\phi}_i^s, \tilde{\varepsilon}_i^{s*}, \tilde{Z}_i, \tilde{\lambda}_i^s, \tilde{\lambda}_i^b\}_{i\in\mathbb{M}}$ proposed in the statement of the proposition satisfies the equilibrium conditions (100)-(104). The inflation rate is the same in both economies since (87) is the same as (95). The expression for the nominal rate in the economy with open-market operations follows from the fact that $q_i = \tilde{\lambda}_i^b/\omega_i$. Finally, notice (101) can be written as

$$Z_i = \frac{\bar{\beta}}{\mu_i} \sum_{j\in\mathbb{M}} \sigma_{ij}(1 + \tilde{r}_j) Z_j,$$

which for $\sigma_{ii} \approx 1$ implies $\tilde{r}_i \approx r_i$, where r_i is the nominal rate corresponding the economy with no bonds, given by (27). ■

D Supplementary material: related literature

The empirical component of our paper (Section 6) 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) 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.[50]

[50] In 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.

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).