Government Intervention and Strategic Trading in the U.S. Treasury Market

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Abstract

We study the impact of outright (permanent) open market operations (POMOs) by the Federal Reserve Bank of New York (FRBNY) on Treasury market microstructure. POMOs are trades in U.S. Treasury securities aimed at maintaining conditions in the market for bank reserves consistent with the Federal Reserve's target level of the federal funds rate. Using a parsimonious model of speculative trading, we show that so-motivated government intervention *improves* market liquidity, by an extent depending on the market's information environment. Evidence from a novel sample of all FRBNY's POMOs between 2001 and 2007 indicates that bid-ask spreads of on-the-run Treasury securities *decline* when POMOs are executed, by an amount increasing in proxies for information heterogeneity among speculators, fundamental volatility, and POMO policy uncertainty, consistent with our model.

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1 Introduction

During the recent financial crisis several Central Banks (most notably, the Federal Reserve and the European Central Bank) traded large amounts of securities. While the motives and effectiveness of these trades continue to be intensely debated (e.g., see Acharya and Richardson, 2009), the potential externalities of these trades on the "quality" of the process of price formation have received much less attention.

In this paper we investigate, both theoretically and empirically, the effects of direct government intervention in a financial market (like Central Bank trades of securities) on that market's microstructure. We do so by studying one market in which monetary authorities have long been active, the secondary market for U.S. government bonds. U.S. Treasury securities are widely held and traded by domestic and foreign investors. The secondary market for these securities is among the largest, most liquid financial markets. There, the Federal Reserve (through its New York branch) routinely buys or sells Treasury securities on an outright basis — with trades known as permanent open market operations (POMOs) — to permanently add or drain *bank reserves* toward a *target* level consistent with the federal funds target rate set by the Federal Open Market Committee (FOMC). The frequency and magnitude of POMO trades are significant: Between January 2001 and December 2007, the Federal Reserve Bank of New York (FRBNY) executed POMOs nearly once every eight working days (see Figure 3), for an average daily principal amount of \$1.11 billion. Importantly, while the FOMC's rate decisions are public and informative about its current and planned stance of monetary policy, the Federal Reserve's targeted level of reserves has been *non-public* and *uninformative* about that stance since the mid-1990s (Akhtar, 1997).[1] This constitutes a crucial difference between POMOs and government interventions in currency markets, the latter being typically deemed informative about economic policy or fundamentals (e.g., Sarno and Taylor, 2001; Payne and Vitale, 2003; Dominguez, 2006).

To guide our analysis of the impact of POMOs on the Treasury market, we develop a model of trading based on Kyle (1985) and Pasquariello and Vega (2007). This model aims to capture parsimoniously an important feature of that market — one highlighted by several empirical studies (e.g., Brandt and Kavajecz, 2004; Green, 2004; Pasquariello and Vega, 2007, 2009) — namely the informational role of trading in Treasury securities for their process of price formation. In the model's basic setting, strategic trading in a risky asset by privately, heterogeneously informed speculators leads uninformed market-makers (MMs) to worsen that asset's equilibrium market liquidity. More valuable or diverse information among speculators magnifies this effect

[1] See also the FRBNY's website at http://www.newyorkfed.org/markets/pomo/display/index.cfm.

by making their trading activity more cautious and MMs more vulnerable to adverse selection.

The introduction of a stylized Central Bank consistent with the nature of the Federal Reserve's POMO policy in this setting significantly alters equilibrium market quality. We model the Central Bank as an informed agent facing a trade-off between policy motives (a non-public and uninformative price target for the risky asset) and the expected cost of its intervention, in the spirit of Stein (1989), Bhattacharya and Weller (1997), Vitale (1999), and Pasquariello (2010). In particular, the price target is a modelling device for the FRBNY's objective of targeting the supply of nonborrowed reserves by trading in Treasury securities in a market where demand for these securities is elastic.[2] We then show that allowing such a Central Bank to trade alongside noise traders and speculators *improves* equilibrium market liquidity. Intuitively, the presence of a Central Bank ameliorates adverse selection concerns for the MMs, not only because a portion of its trading activity is uninformative about fundamentals but also because that activity induces speculators to trade less cautiously on their private signals. This insight differs markedly from those in the aforementioned literature on the microstructure of government intervention in currency markets. In many of those studies (e.g., Bossaerts and Hillion, 1991; Vitale, 1999; Naranjo and Nimalendran, 2000), the Central Bank is typically assumed to act as the *only* informed agent. Thus, its presence generally leads to *deteriorating* market liquidity.[3] Other studies (e.g., Evans and Lyons, 2005; Chari, 2007; Pasquariello, 2010) postulate that uninformative government intervention *worsens* market liquidity because of inventory management considerations, absent from our model by construction.

A further, interesting (and novel) insight of our model is that the magnitude of the improvement in market liquidity stemming from the Central Bank's trading activity is sensitive to the information environment of the market. Specifically, we show that this effect is greater the more volatile are the economy's fundamentals and the more heterogeneous are speculators' private signals about them. As we discussed above, either circumstance worsens market liquidity, but less so when the MMs perceive the threat of adverse selection as less serious because the Central

[2] E.g., see Krishnamurthy (2002), Vayanos and Vila (2009), Greenwood and Vayanos (2010), and Krishnamurthy and Vissing-Jorgensen (2010). We discuss this issue further in Sections 2.2 and 3.1.

[3] See also the surveys in Lyons (2001) and Neely (2005). Similar implications ensue from Oded (2009), who models firms' open-market stock repurchase activity. Bond and Goldstein (2010) show that the introduction of an informed government attempting to reduce a firm's fundamental volatility in a Grossman and Stiglitz (1980) model populated by heterogeneously informed speculators lowers equilibrium price informativeness of that firm's stock. Pastor and Veronesi (2012) find that, in a general equilibrium model where a government has both economic and non-economic motives, policy changes with more uncertain impact lead to greater stock return volatility. Ulrich (2010) explores the implications of Knightian uncertainty about FOMC interventions in the business cycle for the slope of the yield curve and bond risk premiums.

Bank is intervening. Accordingly, we also show that greater uncertainty among market participants about the Central Bank's policy target magnifies its trades' positive liquidity externalities. Greater such uncertainty both makes it more difficult for the MMs to learn about the uninformative policy target from the order flow and alleviates their perceived adverse selection from trading with the privately informed speculators.

We assess the empirical relevance of our model using a comprehensive, recently available sample of intraday price formation in the secondary U.S. Treasury bond market from BrokerTec — the electronic platform where the majority of such trading migrated since its inception (Mizrach and Neely, 2006, 2009; Fleming and Mizrach, 2009)[4] — and a proprietary dataset of all POMOs conducted by the FRBNY between January 2001 and December 2007. POMOs are typically aimed at specific maturity segments of the yield curve, rather than at specific securities. Thus, we focus on the most liquid Treasury securities in those segments — on-the-run (i.e., most recently issued, or benchmark) two-year, three-year, five-year, and ten-year Treasury notes, and thirty-year Treasury bonds.

Our empirical analysis provides strong support for our model's main predictions. First, univariate and multivariate tests show that bid-ask price spreads for notes and bonds nearly uniformly *decline* (i.e., their liquidity *improves*) from prior near-term levels, both on days when the FRBNY executed POMOs in the corresponding maturity bracket and on days when any POMO occurred. The latter may be due to the relatively high degree of substitutability (and ensuing cross-elasticity) among Treasury securities (e.g., Cohen, 1999; D'Amico and King, 2010; Greenwood and Vayanos, 2010). Estimated liquidity improvements are both economically and statistically significant. For instance, on any-maturity POMO days quoted bid-ask spreads are on average 7% (for three-year notes) to 16% (for five-year notes) lower than their sample means, and 25% (for thirty-year bonds) to 46% (for two-year notes) lower than the sample standard deviation of their daily changes.

This evidence is unlikely to stem from POMOs' impact on reserve market conditions (e.g., funding liquidity; Brunnermeier and Pedersen, 2009), search costs (e.g., Vayanos and Weill, 2008), or the aforementioned migration to electronic trading for *i)* it is robust to controlling for various calendar and bond fixed effects; *ii)* it is obtained over a sample period when the FRBNY neither sold Treasury security nor traded in "scarce" ones; *iii)* it is unaffected by extending our sample to the financial crisis of 2008 and 2009, i.e., despite the crisis' implications for liquidity

[4]For instance, Mizrach and Neely (2006) report that 61% of trading volume in on-the-run Treasury securities in 2004 occurred in BrokerTec, with eSpeed — a competing platform launched by Cantor Fitzgerald — accounting for the remaining 39%. Most trading in off-the-run Treasury securities still occurs through voice-assisted brokers (and is recorded by GovPX).

provision and the nature of the FRBNY's intervention activity in the Treasury market; and *iv)* it is reproduced over a partly overlapping sample of quotes on the previously dominating, voice-brokered GovPX platform. Importantly, since bid-ask spreads in the Treasury market do not affect the FRBNY's stated reserve policy, its POMOs are likely to be exogenous to their event-day levels and dynamics.

Second, our analysis also reveals that the magnitude of POMOs' positive liquidity externalities is related to the informational role of trading in the Treasury market, uniquely consistent with our model. We find that bid-ask spreads decline significantly more *i)* the worse is Treasury market liquidity, i.e., especially in the earlier portion of the sample (2001-2004); *ii)* the greater is marketwide dispersion of beliefs about U.S. macroeconomic fundamentals (measured by the standard deviation of professional forecasts of macroeconomic news releases); *iii)* the greater is marketwide uncertainty surrounding U.S. macroeconomic fundamentals (measured by Eurodollar implied volatility); and *iv)* the greater is marketwide uncertainty surrounding the Federal Reserve's POMO policy (measured by federal funds rate volatility).

Open market operations (OMOs) have received surprisingly little attention in the literature. In the only published empirical study on the topic we are aware of, Harvey and Huang (2002) find that the FRBNY's OMOs between 1982 and 1988 — when those trades were still deemed informative about the Federal Reserve's monetary policy stance — are, on average, accompanied by higher intraday T-Bill, Eurodollar, and T-Bond futures return volatility. Harvey and Huang (2002) conjecture that such increase may be attributed to the effect of OMOs on market participants' expectations.[5] This evidence is consistent with that from several studies of the impact of potentially informative Central Bank interventions on the microstructure of currency markets (e.g., Dominguez, 2003, 2006; Pasquariello, 2007b). As mentioned above, the focus of our study is on the impact of uninformative Central Bank trades on the microstructure of fixed income markets in the presence of strategic, informed speculation.

We proceed as follows. In Section 2, we construct a stylized model of trading in the presence of an active Central Bank to guide our empirical analysis. In Section 3, we describe the data. In Section 4, we present the empirical results. We conclude in Section 5.

[5] Accordingly, Inoue (1999) finds that informative POMOs by the Bank of Japan are accompanied by higher intraday trading volume and price volatility in the secondary market for ten-year on-the-run Japanese government bonds.

2 A Model of POMOs

The objective of this study is to analyze the impact of permanent open market operations (POMOs) by the Federal Reserve on the liquidity of the secondary U.S. Treasury bond market. Trading in this market occurs in an interdealer over-the-counter setting in which primary and non-primary dealers act as market-makers, trading with customers on their own accounts and among themselves via interdealer brokers.[6] In this section we develop the simplest stylized representation of the process of price formation in the Treasury bond market apt for our objective. First, we describe a parsimonious model of trading in Treasury securities based on Kyle (1985) and Pasquariello and Vega (2007), and derive closed-form solutions for the equilibrium depth as a function of the information environment of the market. Then, we enrich the model by introducing a Central Bank attempting to achieve a policy target while accounting for the cost of the intervention and consider the properties of the ensuing equilibrium. We test for the statistical and economic significance of our theoretical argument in the remainder of the paper. All proofs are in the Appendix.

2.1 The Basic Model

The basic model is a two-date ($t = 0, 1$) economy in which a single risky asset is exchanged. Trading occurs only at date $t = 1$, after which the payoff of the risky asset — a normally distributed random variable v with mean p_0 and variance σ_v^2 — is realized. The economy is populated by three types of risk-neutral traders: A discrete number (M) of informed, risk-neutral traders (henceforth speculators), liquidity traders, and perfectly competitive market-makers (MMs) in the risky asset. All traders know the structure of the economy and the decision process leading to order flow and prices.

At date $t = 0$ there is neither information asymmetry about v nor trading, and the price of the risky asset is p_0. Recent studies suggest that there may be private, heterogeneous information (or interpretation of public information) about the determinants of the future resale value of Treasury securities (e.g., see Brandt and Kavajecz, 2004; Berger et al., 2009). Brandt and Kavajecz (2004), Green (2004), and Pasquariello and Vega (2007, 2009) provide strong evidence of the informational role of trading in the process of price formation in the secondary market for Treasury securities. Accordingly, sometime between $t = 0$ and $t = 1$, we endow each speculator m with a private and noisy signal of v, $S_v(m)$. We assume that each signal $S_v(m)$ is drawn from

[6] For more details on the microstructure of the U.S. Treasury market, see Fabozzi and Fleming (2004) and Mizrach and Neely (2009).

a normal distribution with mean p_0 and variance σ_s^2 and that, for any two speculators m and j, $cov[S_v(m), S_v(j)] = cov[v, S_v(m)] = \sigma_v^2$. We further parametrize the dispersion of speculators' private information by imposing that $\sigma_s^2 = \frac{1}{\rho}\sigma_v^2$ and $\rho \in (0, 1)$.[7] These assumptions imply that each speculator's information advantage about v at $t = 1$, before trading with the MMs, is given by $\delta_v(m) \equiv E[v|S_v(m)] - p_0 = \rho[S_v(m) - p_0]$, and that $E[\delta_v(j)|\delta_v(m)] = \rho\delta_v(m)$. The parameter ρ can be interpreted as the correlation between any two information endowments $\delta_v(m)$ and $\delta_v(j)$: The lower (higher) is ρ, the more (less) *heterogeneous* — i.e., the less (more) correlated and, of course, precise — is speculators' private information about v.

At date $t = 1$, both liquidity traders and speculators submit their orders to the MMs before the equilibrium price p_1 has been set. We define the market order of each speculator m as $x(m)$, such that her profit is given by $\pi(m) = (v - p_1)x(m)$. Liquidity traders generate a random, normally distributed demand z, with mean zero and variance σ_z^2. For simplicity, we assume that z is independent from all other random variables. The uninformed MMs observe the ensuing aggregate order flow $\omega_1 = \sum_{m=1}^{M} x(m) + z$ and then set the market-clearing price $p_1 = p_1(\omega_1)$. Consistently with Kyle (1985), we define a Bayesian Nash equilibrium of this economy as a set of $M + 1$ functions $x(m)(\cdot)$ and $p_1(\cdot)$ such that the following two conditions hold:

1. *Utility maximization*: $x(m)(\delta_v(m)) = \arg\max E[\pi(m)|\delta_v(m)]$;

2. *Semi-strong market efficiency*: $p_1(\omega_1) = E(v|\omega_1)$.[8]

The following proposition characterizes the unique linear, rational expectations equilibrium for this economy satisfying Conditions 1 and 2.

Proposition 1 *There exists a unique linear equilibrium given by the price function*

$$p_1 = p_0 + \lambda\omega_1 \tag{1}$$

and by each speculator m's demand strategy

$$x(m) = \frac{\sigma_z}{\sigma_v\sqrt{M\rho}}\delta_v(m), \tag{2}$$

where

$$\lambda = \frac{\sigma_v\sqrt{M\rho}}{\sigma_z[2 + (M-1)\rho]} > 0. \tag{3}$$

[7] The analysis that follows yields similar implications, albeit at the cost of greater analytical complexity, if based on more general information structures — e.g., $cov[v, S_v(m)] \neq cov[S_v(m), S_v(j)]$ and $cov[v, S_v(m)] \neq \sigma_v^2$ (see Foster and Viswanathan, 1996; Pasquariello, 2007a; Pasquariello and Vega, 2007; Albuquerque and Vega, 2009).

[8] Equivalently, competition is assumed to force MMs' expected profits to zero.

In equilibrium, imperfectly competitive speculators, despite being risk-neutral, trade on their private information cautiously ($|x(m)| < \infty$) to reduce the dissipation of their informational advantage. Thus, speculators' optimal trading strategies depend both on their information endowments about the traded asset's payoff v ($\delta_v(m)$) and market liquidity (λ): $x(m) = \frac{1}{\lambda[2+(M-1)\rho]}\delta_v(m)$. As in Kyle (1985), a positive λ allows MMs to offset losses from trading with speculators with profits from noise trading (z). As such, liquidity deteriorates (λ is greater) the more uncertain is the traded asset's payoff v (higher σ_v^2), for the greater is speculators' information advantage and the more vulnerable MMs are to adverse selection. Importantly, $x(m)$ and λ also depend on ρ, the correlation among speculators' information endowments. Intuitively, these speculators, being imperfectly competitive, act noncooperatively to exploit their private information. As in Pasquariello and Vega (2007), when such information is more heterogeneous (ρ closer to zero), each speculator perceives to have greater monopoly power on her signal, because at least part of it is perceived to be known exclusively to her. Hence, each speculator trades more cautiously — i.e., her market order is lower: $\frac{\partial|x(m)|}{\partial\rho} = \frac{\sigma_z}{2\sigma_v\rho\sqrt{M\rho}}|\delta_v(m)| > 0$ — to reveal less of her information endowment. Lower trading aggressiveness makes the aggregate order flow less informative and the adverse selection of MMs more severe, worsening equilibrium market liquidity (higher λ). The following corollary summarizes these basic properties of λ of Eq. (3).

Corollary 1 *Equilibrium market liquidity is decreasing in σ_v^2 and ρ.*

Pasquariello and Vega (2007, 2009) find strong empirical support for the predictions of our model in the U.S. Treasury market (see also Fleming, 2003; Brandt and Kavajecz, 2004; Green, 2004; Li et al., 2009).

2.2 Central Bank Intervention

The Federal Reserve routinely intervenes in the secondary U.S. Treasury market via open market operations (OMOs) to implement its monetary policy.[9] OMOs are trades in previously issued U.S. Treasury securities executed by the *Open Market Desk* ("the Desk") at the Federal Reserve Bank of New York (FRBNY), on behalf of the entire Federal Reserve System, to ensure that

[9] To that end, the Federal Reserve may also change its reserve requirements on the checkable deposits of commercial banks and thrift institutions and/or the discount rate for *borrowed* reserves from its discount window. Akhtar (1997), Harvey and Huang (2002), and Afonso et al. (2010) provide detailed discussions of U.S. monetary policy and implementation. Further information is also available on the FRBNY website at http://www.newyorkfed.org/markets/openmarket.html.

the supply of nonborrowed reserves in the banking system is consistent with the target for the federal funds rate set by the Federal Open Market Committee (FOMC).

The federal funds rate is the rate clearing the federal funds market, the market where financial institutions trade *reserves* — non-interest bearing deposits held by those institutions at the Federal Reserve — on a daily basis.[10] Purchases (sales) of government bonds by the Desk expand (contract) the aggregate supply of *nonborrowed* reserves — i.e., those not originating from the Federal Reserve's discount window (which is meant as a source of last resort) — in the monetary system. Thus, if the FRBNY expects *persistent* imbalances in the federal funds market (e.g., due to trends in the demand for money by the economy) relative to the FOMC's target rate, it may affect the supply of nonborrowed reserves through *outright* (or *permanent*) trades of government bonds (POMOs).[11] If those imbalances are instead expected to be *temporary*, the FRBNY may enter repurchasing agreements (TOMOs) by which it either buys (*repos*) or sells (*reverse repos* or *matched-sale purchases*) government bonds with the agreement to an equivalent transaction of the opposite sign at a specified price and on a specified later date (typically one trading day later).[12] Accordingly, TOMOs occur much more frequently (nearly every trading day) than POMOs.

Importantly, since February 1994 the FOMC has made its monetary policy decisions increasingly transparent — e.g., by pre-announcing its intentions and disclosing the federal funds target rate — therefore making the Desk's OMOs virtually uninformative about the Federal Reserve's future monetary policy stance over our sample period (Akhtar, 1997; Harvey and Huang, 2002).[13] Yet, while the FOMC's target federal funds rate is publicly announced to all market participants, the actions by the Desk at the FRBNY are all but "mechanical" (Akhtar, 1997,

[10] See Furfine (1999) for a detailed analysis of the microstructure of the federal funds market.

[11] For instance, according to Akhtar (1997, p. 18), "currency demand is the largest single factor requiring reserve injections [i.e., POMO purchases], because it has a strong growth trend which reflects, primarily, the growth trend of the economy."

[12] For the same purpose, the FRBNY less often trades in *agency debt* (i.e., issued by Fannie Mae, Freddie Mac, or Federal Home Loan Banks) and agency *mortgage-backed securities* (i.e., guaranteed by Fannie Mae, Freddie Mac, or Ginnie Mae). The FRBNY also executes customer-related outright trades, repos, and reverse repos directly with foreign official accounts, usually to satisfy very small and/or temporary reserve imbalances. As such, these *customer transactions* constitute a much less important tool of the Federal Reserve's monetary policy than their standard counterparts, and have only occasionally been arranged since December 1996 (see Akhtar, 1997).

[13] For instance, Akhtar (1997, p. 46, emphasis is ours) observes that the disclosure procedures initiated by the FOMC in early 1994 and formalized in early 1995 "have essentially freed the [FRBNY] from the risk that its normal technical or defensive operations would be misinterpreted as policy moves. *Open market operations no longer convey any new information about changes in the stance of monetary policy.*"

p. 34). Given that target rate, the timing, direction, and magnitude of FRBNY trades along the Treasury maturity structure are driven by nonborrowed reserve paths (or *reserve targets*) based on its projections of current and future reserve excesses or shortages — as well as by its assessment of current and future U.S. Treasury market conditions — in an environment in which those reserve imbalances are subject to many factors outside of the Central Bank's control (e.g., see Harvey and Huang, 2002). This implies that at any point in time there may be considerable uncertainty among market participants as to the nature of the trading activity by the FRBNY in the secondary U.S. Treasury market, i.e., about its reserve targets.[14]

In this study we intend to analyze the process of price formation in the Treasury market in the presence of outright trades (i.e., POMOs) by the FRBNY's Desk. To that purpose, we amend the basic one-shot model of trading of Section 2.1 to allow for the presence of a stylized Central Bank alongside speculators and liquidity traders. As such, this setting is inadequate at capturing TOMOs' transitory nature and significantly higher recurrence.[15] We model the main features of FRBNY's POMO policy in a parsimonious fashion by assuming that *i)* sometime between $t = 0$ and $t = 1$, the Central Bank is given a *non-public* price target p_T for the traded asset, drawn from a normal distribution with mean $\overline{p}_T$ and variance σ_T^2; and *ii)* at date $t = 1$, before the equilibrium price p_1 has been set, the Central Bank submits to the MMs an outright market order x_{CB} minimizing the expected value of the following separable loss function:

$$L = \gamma \left(p_1 - p_T\right)^2 + (1 - \gamma)\left(p_1 - v\right) x_{CB}, \tag{4}$$

where $\gamma \in (0, 1)$ is common knowledge. The specification of Eq. (4) is similar in spirit to Stein (1989), Bhattacharya and Weller (1997), Vitale (1999), and Pasquariello (2010).[16] The first component captures the FRBNY's policy motives in its trading activity by the squared distance between the traded asset's equilibrium price p_1 and the target p_T. The *price target* captures the Desk's efforts to target the *supply* of nonborrowed reserves — via outright purchases or sales of Treasury securities affecting dealers' deposits at the Federal Reserve — while facing an elastic *demand* for Treasury securities (e.g., Krishnamurthy, 2002; Vayanos and Vila, 2009; Greenwood

[14] This uncertainty persists even when the Federal Reserve explicitly announces its intentions to execute OMOs in the near future. We discuss these rare circumstances in Section 3.2.

[15] Sokolov (2009) examines the effect of overnight TOMOs executed by the FRBNY in 2000 on intraday volatility and liquidity of two-year and five-year on-the-run Treasury notes.

[16] See also Kumar and Seppi (1992) and Hanson and Oprea (2009) for models of price manipulation in futures and prediction markets, respectively. When studying interbank market freezes, Allen et al. (2009) model Central Bank's OMOs in long-term riskless assets as providing opportunities for financial institutions to hedge aggregate and idiosyncratic liquidity shocks in the interbank market.

and Vayanos, 2010; Krishnamurthy and Vissing-Jorgensen, 2010).[17] The second component captures the cost of the intervention as any deviation from purely speculative trading motives.[18] Finally, the ratio $d \equiv \frac{\gamma}{1-\gamma}$ captures the relative degree of FRBNY's commitment to its policy objectives.

The FRBNY is likely to have first-hand knowledge of macroeconomic fundamentals. Thus, we assume that the Central Bank is also given a private signal of the risky asset's payoff v, S_{CB} — a normally distributed variable with mean p_0 and variance $\sigma^2_{CB} = \frac{1}{\psi}\sigma^2_v$, where the precision parameter $\psi \in (0,1)$ and $cov\left[S_v\left(m\right), S_{CB}\right] = cov\left(v, S_{CB}\right) = \sigma^2_v$ (as for $S_v\left(m\right)$ in Section 2.1). However, since (as mentioned above) the FOMC does not employ POMOs to communicate changes in its stance of monetary policy to financial markets, we further impose that the policy target p_T is *uninformative* about v, i.e., that $cov\left(v, p_T\right) = cov\left[S_v\left(m\right), p_T\right] = cov\left(S_{CB}, p_T\right) = 0$.[19] Both uncertainty about and uninformativeness of p_T are meant to capture the unanticipated nature of FRBNY trades in government bonds in the wake of public, informationally rich FOMC rate decisions.[20]

In our setting, we can think of these policy decisions as translating into the commonly known distribution of the risky asset's liquidation payoff v given at date $t = 0$. This distribution is *independent* of the FRBNY's subsequent trading activity in that asset. Thus, our assumptions about p_T reflect the uncertainty surrounding the FRBNY's practical implementation of the announced informative FOMC policy in the marketplace (e.g., about the Desk's uninformative

[17] Intuitively, in the presence of downward sloping demand curves for Treasury securities, changes in their supply induced by the Desk's outright trades affect their prices. Hence, ceteris paribus, the Desk's reserve targets can be represented as either Treasury price targets or Treasury supply targets. In our stylized setting, we choose the former for analytical convenience.

[18] Intuitively, if $\gamma = 0$, the Central Bank would trade as just another speculator (i.e., would maximize the expected profit from trading the risky asset at p_1 before its payoff v is realized). Hence, deviating from optimal speculation to pursue policy is costly. The restriction that $0 < \gamma < 1$ in Eq. (4) then ensures that the Central Bank does not trade unlimited amounts of the risky assets to achieve its policy target p_T. See also the discussion in Bhattacharya and Weller (1997) and Vitale (1999).

[19] Importantly, it can be shown that our model's implications are qualitatively unaffected (yet its analysis is more analytically involved) by making the Central Bank's policy target p_T at least *partially* correlated with the traded asset's fundamentals (as in Bhattacharya and Weller, 1997).

[20] With knowledge of Eq. (4), rational MMs would account for any trading activity driven by a public, uninformative policy target p_T, thus making the Desk's efforts ineffective (Vitale, 1999). Credible, informative announcements about asset fundamentals (v), like those by the FOMC, would immediately be incorporated into market participants' expectations and equilibrium prices. However, if asset fundamentals are given, as for the FRBNY's Desk since 1994, no announcement about its uninformative target p_T would be deemed credible. For more on the economics of disclosing public information as an information choice problem see, e.g., Stein (1989), Bond and Goldstein (2010), and Veldkamp (2011).

targets for nonborrowed reserves). These assumptions also imply that the Central Bank's information endowments about v and p_T at $t = 1$, before trading with the MMs, are given by $\delta_{CB} \equiv E(v|S_{CB}) - p_0 = \psi(S_{CB} - p_0)$ and $\delta_T \equiv p_T - \overline{p}_T$, respectively.

As in Section 2.1, the MMs set the equilibrium price p_1 at date $t = 1$ after observing the aggregate order flow made of the market orders of liquidity traders, speculators, and the Central Bank, $\omega_1 = x_{CB} + \sum_{m=1}^{M} x(m) + z$. Proposition 2 accomplishes the task of solving for the unique linear Bayesian Nash equilibrium of this economy.

Proposition 2 *There exists a unique linear equilibrium given by the price function*

$$p_1 = [p_0 + 2d\lambda_{CB}(p_0 - \overline{p}_T)] + \lambda_{CB}\omega_1, \tag{5}$$

by each speculator m's demand strategy

$$x(m) = \frac{2(1 + d\lambda_{CB}) - \psi}{\lambda_{CB}\{2[2 + (M-1)\rho](1 + d\lambda_{CB}) - M\psi\rho(1 + 2d\lambda_{CB})\}}\delta_v(m), \tag{6}$$

and by the Central Bank's demand strategy

$$\begin{aligned} x_{CB} &= 2d(\overline{p}_T - p_0) + \frac{d}{1 + d\lambda_{CB}}\delta_T \\ &\quad + \frac{[2 + (M-1)\rho] - M\rho(1 + 2d\lambda_{CB})}{\lambda_{CB}\{2[2 + (M-1)\rho](1 + d\lambda_{CB}) - M\psi\rho(1 + 2d\lambda_{CB})\}}\delta_{CB}, \end{aligned} \tag{7}$$

where λ_{CB} is the unique positive real root of the sextic polynomial of Eq. (A-25) in the Appendix.

In equilibrium, each speculator m accounts not only for the potentially competing trading activity of the other speculators (as in the equilibrium of Proposition 1) but also for the trading activity of the Central Bank when setting her cautious optimal demand strategy $x(m)$ to exploit her information advantage $\delta_v(m)$. As such, $x(m)$ of Eq. (6) also depends on the commonly known parameters controlling the government's intervention policy — the quality of its private information (ψ), the uncertainty surrounding its policy target (σ_T^2), and its commitment to it (d).

Similarly, the Central Bank accounts for the information environment of the market — the number of speculators (M) and the heterogeneity of their private information (ρ) — when devising its optimal trading strategy x_{CB}. This strategy, as described by Eq. (7), is made of three terms. The first one depends on the expected deviation of the policy target p_T from the equilibrium price in absence of government intervention, and is fully anticipated by the MMs when setting the market-clearing price p_1 of Eq. (5). The second one depends on the portion of that target that is known exclusively to the Central Bank, δ_T; ceteris paribus, the more liquid is the market (the lower is λ_{CB}), the more aggressively the Central Bank trades on δ_T to achieve its policy objectives — the more so the more important is the gap between p_1 and p_T in its loss function (the higher is d). The third one depends on the Central Bank's attempt at minimizing the expected cost of the intervention given its private fundamental information δ_{CB}; as such, it may either amplify or dampen its magnitude.

According to Abel's Impossibility Theorem, the sixth degree polynomial yielding λ_{CB} cannot be solved using rational operations and finite root extractions. Therefore, we find its unique positive real root using the three-stage algorithm proposed by Jenkins and Traub (1970a, b) and characterize the properties of the resulting equilibrium of Proposition 2 by means of numerical examples (with "reasonable" parameter values) rather than formal comparative statics.[21] To that purpose, we set $\sigma_v^2 = \sigma_z^2 = \sigma_T^2 = 1$, $\rho = 0.5$, $\psi = 0.5$, $\gamma = 0.5$, and $M = 500$. We then plot the ensuing difference between equilibrium price impact in the presence and in the absence of the stylized Central Bank of Eq. (4) — $\Delta\lambda \equiv \lambda_{CB} - \lambda = \lambda_{CB} - \frac{\sigma_v \sqrt{M\rho}}{\sigma_z[2+(M-1)\rho]}$ — as a function of either γ, σ_T^2, ρ, or σ_v^2, in Figures 1a to 1d, respectively (continuous lines).

First, government intervention improves market liquidity: $\Delta\lambda < 0$ in Figure 1. Intuitively, the Central Bank's optimal trading strategy stems from the resolution of a trade-off between pursuing a non-public, uninformative target (p_T) and the cost of deviating from optimal informed speculation ($x_{CB} = \frac{2-\rho}{\lambda_{CB}\{2[2+(M-1)\rho]-M\psi\rho\}}\delta_{CB}$ when $\gamma = 0$). The former leads the Central Bank to trade more (or less) than it otherwise would given the latter to achieve its policy target. Hence, a portion of its trading activity in Eq. (7) is uninformative about fundamentals (v). Further uninformative trading in the order flow also induces the speculators to trade more aggressively on their private signals.[22] Both in turn imply that the MMs perceive the threat of adverse selection as less serious than in the absence of the Central Bank, so making the market more liquid. Along those lines, equilibrium market liquidity is better (and $\Delta\lambda$ is more negative) the greater is either the Central Bank's policy commitment (i.e., for higher γ in Figure 1a) or the uncertainty surrounding its policy (i.e., for higher σ_T^2 in Figure 1b), since in both circumstances the greater is the perceived intensity of uninformative government trading in the aggregate order

[21] E.g., in light of the above discussion on the FRBNY's POMO policy, "reasonable" parametrizations of our model are those in which the Central Bank is sufficiently committed to its uninformative policy target p_T (i.e., γ is sufficiently high) and there is sufficient uncertainty surrounding that target among market participants (i.e., σ_T^2 is sufficiently high).

[22] I.e., Propositions 1 and 2 imply that $x(m)$ of Eqs. (2) and (6) can be rewritten as $x(m) = B_1\rho[S_v(m) - p_0]$; it can then be shown that $\Delta B_1\rho \equiv \frac{\rho[2(1+d\lambda_{CB})-\psi]}{\lambda_{CB}\{2[2+(M-1)\rho](1+d\lambda_{CB})-M\psi\rho(1+2d\lambda_{CB})\}} - \frac{\rho\sigma_z}{\sigma_v\sqrt{M\rho}} > 0$. Accordingly, unreported analysis also shows that $\Delta\lambda$ is more negative in the presence of fewer speculators (i.e., for smaller M), since their trading activity is more cautious and the market in absence of government intervention less liquid.

flow.[23]

Second, the extent of this improvement in market liquidity is sensitive to the information environment of the market. In particular, $|\Delta\lambda|$ is increasing in the heterogeneity of speculators' signals (i.e., for lower ρ in Figure 1c) and in the economy's fundamental uncertainty (i.e., for higher σ_v^2 in Figure 1d). As discussed in Section 2.1, less correlated (ρ closer to zero) or more valuable (higher σ_v^2) private information enhances speculators' incentives to behave cautiously when trading.[24] This worsens market liquidity regardless of whether the Central Bank is intervening or not, yet less so when it is doing so, i.e., when adverse selection is already less severe. Thus, the liquidity differential increases. The following remark summarizes the aforementioned implications of our numerical examples.

Remark 1 *There exists a nonempty set of reasonable parameter values such that, in the presence of a Central Bank, $\Delta\lambda$ is negative and $|\Delta\lambda|$ is increasing in γ, σ_T^2, and σ_v^2, and decreasing in ρ.*

3 Data Description

We test the implications of the model of Section 2 in a comprehensive sample of intraday price formation in the secondary U.S. Treasury bond market, and of open market operations executed by the Federal Reserve Bank of New York.

3.1 Bond Market Data

We use intraday, interdealer U.S. Treasury bond price quotes from BrokerTec for the most recently issued (i.e., *benchmark*, or *on-the-run*) two-year, three-year, five-year, and ten-year Treasury notes, and thirty-year Treasury bonds between January 2, 2001 and December 31, 2007. Our sample period does not encompass the financial turmoil stemming from the collapse of Bear Sterns and Lehman Brothers in 2008, as well as the accompanying open market operations by the FRBNY in 2009. Improving marketwide liquidity provision may be an important concern behind the FRBNY's trading activity in the secondary market for Treasury securities during times of crisis and market stress. Our model is not designed to capture those circumstances nor

[23] It can also be shown that the efforts of the Central Bank are *successful* in the equilibrium of Proposition 2, if we define the *effectiveness* of government intervention in our economy to be the unconditional covariance between the equilibrium price p_1 and its uninformative target p_T: $cov(p_1, p_T) = \frac{d\lambda_{CB}}{1+d\lambda_{CB}}\sigma_T^2 > 0$. Intuitively, the uncertainty surrounding the Central Bank's policy ($\sigma_T^2 > 0$) prevents the MMs from fully accounting for the government intervention when setting the market-clearing price after observing the aggregate order flow ω_1.

[24] E.g., unreported analysis shows that $|\Delta B_1 \rho|$ is increasing in ρ.

the unique nature of these trades.[25] Unreported analysis shows our inference to be unaffected by this exclusion. Further, our sample period allows for the widest coverage of price formation at the most relevant segments of the yield curve.[26] We focus on on-the-run issues because those securities display the greatest liquidity and informed trading (e.g., Fleming, 1997; Brandt and Kavajecz, 2004; Goldreich et al., 2005; Pasquariello and Vega, 2007). Trading in more seasoned (i.e., *off-the-run*) Treasury securities is scarce, and their liquidity more difficult to assess (Fabozzi and Fleming, 2004; Pasquariello and Vega, 2009).

Since the early 2000s, interdealer trading in benchmark Treasury securities has migrated from voce-assisted brokers (whose data are consolidated by GovPX) to either of two fully electronic trading platforms, BrokerTec (our data source) and eSpeed. BrokerTec accounts for nearly two-thirds of such trading activity (Mizrach and Neely, 2006). Fleming and Mizrach (2009) find that liquidity and trading volume in BrokerTec are significantly greater than what reported in earlier studies of the secondary Treasury bond market based on GovPX data. Within BrokerTec, brokers provide electronic screens displaying, for each security (i), the best five bid (B_i) and ask (A_i) prices and accompanying quantities; traders either enter limit orders or hit these quotes anonymously.[27] Our sample includes every quote posted during "New York trading hours," from 7:30 a.m. ("open") to 5:00 p.m. ("close") Eastern Time (ET).[28] To eliminate interdealer brokers' posting errors, we filter all quotes within this interval following the procedure described in Fleming (2003).[29] Lastly, we augment the BrokerTec database with information on important

[25] For instance, and contrary to its established *modus operandi* (see Section 3.2), the Federal Reserve announced its intention to execute POMOs (and some details about their characteristics) in advance at the March 2009 FOMC meeting, when it directed the Desk to purchase up to $300 billion of long-term Treasury securities over the subsequent six months. The Desk executed this policy program — known as Large-Scale Asset Purchases (LSAP) or "quantitative easing" — over several trading days between March 25 and October 29, 2009. In those circumstances, the Desk first announced the broad maturity segment it targeted and the days in which it was planning to trade — but not the list of securities and par amounts to be auctioned — about two weeks in advance (D'Amico and King, 2010). Afonso et al. (2011) discuss the significant impact of the financial crisis of 2008 on the federal funds market. Hu et al. (2010) provide evidence of severe dislocations in the U.S. Treasury market during crisis periods.

[26] For example, coverage of three-year and ten-year notes, as well as thirty-year bonds, in our BrokerTec database significantly deteriorates after 2007.

[27] BrokerTec and eSpeed have also retained the expanded limit order protocol (e.g., allowing *workups* and *iceberg* orders) previously available with voice-assisted brokers. See Boni and Leach (2004), Mizrach and Neely (2006), Dungey et al. (2009), and Fleming and Mizrach (2009) for investigations of these electronic trading procedures.

[28] Although trading takes place nearly continuously during the week, 95% of trading volume occurs during those hours (e.g., Fleming, 1997). Outside that interval, fluctuations in bond prices are likely due to illiquidity.

[29] We also eliminate federal holidays, days in which BrokerTec recorded unusually low trading activity, and the days immediately following the terrorist attack to the World Trade Center (September 11 to September 21, 2001)

fundamental characteristics (daily modified duration, $D_{i,t}$, and convexity, $C_{i,t}$) of all notes and bonds in our sample (from Morgan Markets).

3.1.1 Measuring Treasury Market Liquidity

The model of Section 2 yields implications of the occurrence of POMOs for the liquidity of the secondary U.S. Treasury bond market. These implications stem from the informational role of speculative trading in the Treasury market for its liquidity. To better capture such role, we focus our analysis on *daily* measures of market liquidity for each security in our sample. Since the econometrician does not observe the precise timing and extent of informed speculation throughout the day, narrowing the estimation window may lead to misestimating its effects on market liquidity in the presence of government intervention. In addition, non-informational microstructure frictions (e.g., bid-ask bounce, quote clustering, price staleness, inventory effects) affecting estimates of intraday market liquidity generally become immaterial over longer horizons (Hasbrouck, 2007).

In the context of our model (based on Kyle, 1985), market liquidity for a traded asset i is defined as the marginal impact of unexpected aggregate order flow on its equilibrium price, λ_i. When transaction-level data is available, this variable is typically estimated as the slope $\lambda_{i,t}$ of the regression of intraday yield or price changes on the unexpected portion of intraday aggregate net volume. While our BrokerTec sample does not include such data, direct estimation of $\lambda_{i,t}$ suffers from several shortcomings. First, the occasional scarcity of trades (but not of posted bid and ask quotes) at certain maturities may make the estimation of $\lambda_{i,t}$ at the daily frequency problematic. Even when possible, this estimation requires the econometrician *i)* to model expected intraday aggregate order flow, as well as *ii)* to explicitly control for the effect of the aforementioned non-informational microstructure frictions on its dynamics (e.g., Green, 2004; Brandt and Kavajecz, 2004; Pasquariello and Vega, 2007). Thus, any ensuing inference may be subject to both misspecification and biases stemming from measurement errors in the dependent variable (e.g., Greene, 1997).

Accordingly, in this paper we measure each benchmark Treasury security's liquidity with the daily (i.e., from open to close) average of its quoted *absolute price* bid-ask spread, $S_{i,t}$. On-the-run spreads are virtually without measurement error. There is an extensive literature relating their magnitude and dynamics to the informational role of trading (see O'Hara, 1995, for a review). Lastly, when comparing several alternative measures of liquidity in the U.S. Treasury market, Fleming (2003) finds that the quoted bid-ask spread is the most highly correlated with both

because of the accompanying significant illiquidity in the Treasury market (e.g., Hu et al., 2010).

direct estimates of price impact and well-known episodes of poor liquidity in that market.[30] The inference that follows is robust *i)* to replacing $S_{i,t}$ with average daily *percentage* bid-ask price spreads, as well as *ii)* to computing $S_{i,t}$ over the ninety-minute intraday interval during which the FRBNY typically executes its POMOs — 10:00 a.m. to 11:30 a.m. ET (see Section 3.2 below). Panel A of Table 1 reports summary statistics for the following variables: Average daily quoted bid-ask spread ($S_{i,t}$) and daily trading volume ($V_{i,t}$) for each of the benchmark Treasury security in our sample. Consistent with market conventions (e.g., Fleming, 2003), Treasury notes and bond prices are in points, i.e., are expressed as a percentage of par multiplied by 100.[31] Thus, bid-ask spreads are in basis points (*bps*), i.e., are further multiplied by 100.[32] We also plot the corresponding time series of $S_{i,t}$ in Figure 2.

The secondary market for on-the-run Treasury notes and bonds is extremely liquid. Average trading volumes are high and quoted bid-ask spreads are small; both are close to what reported in other studies (e.g., Fleming, 2003; Fleming and Mizrach, 2009, among others). Not surprisingly, bid-ask spreads display large positive first-order autocorrelation ($\rho(1) > 0$). Notably, Figure 2 suggests that bid-ask spreads are wider in the earlier portion of the sample (2001-2004), before sharply declining afterwards (2005-2007). Corresponding summary statistics (in Panels B and C of Table 1, respectively) confirm this pattern in Treasury bond market liquidity. We discuss and address its implications for our analysis in Section 4.1. Data for three-year notes has significant gaps in BrokerTec market coverage, restricting our analysis of that maturity segment to the sub-period 2003-2007. Figure 2 also reveals occasional gaps in coverage for ten-year notes and thirty-year bonds. Bid-ask spreads for Treasury securities are decreasing (and their liquidity is generally increasing) with their maturity.[33] Two-year Treasury notes are characterized by the highest average daily trading volume ($21 billion) and the smallest average spread, 1.096 bps (i.e., 1.096 percent of one point). The latter implies an average roundtrip cost of about $\$22,000$ for trading $200 million par notional of these notes, an amount routinely available on BrokerTec

[30] See also Chordia et al. (2005) and Goldreich et al. (2005). Data availability considerations preclude us from pursuing any of the techniques available in the literature to separate the portion of the bid-ask spread due to adverse selection from those due to order processing costs or inventory control (e.g., Stoll, 1989; George et al., 1991). In any case, execution costs are likely to be stable over time, hence to cancel out when computing bid-ask spread changes, as we do in the analysis that follows

[31] One point is one percent of par. In BrokerTec, prices of notes and bonds are instead quoted in 32^{nds} of a point; the tick size is one quarter of a 32^{nd} for two-year, three-year, and five-year notes, and one half of a 32^{nd} for ten-year notes and thirty-year bonds. However, the BrokerTec database reports all prices in 256^{ths} of a point.

[32] One basis point is one percent of one point.

[33] Proportional bid-ask spreads display the same pattern, since on-the-run bond prices at all maturities (except at the very long end of the yield curve) tend to be relatively close to par over our sample period.

at the best bid and ask prices (Fleming and Mizrach, 2009). BrokerTec bid-ask spreads for thirty-year Treasury bonds are not only the highest among the securities in our sample (8.322 bps, or $166,440 per $200 million face value), but also higher than those typically observed in the eSpeed platform (e.g., Mizrach and Neely, 2006). This may reflect the historical dominance of Cantor Fitzgerald — eSpeed's founder — in interdealer trading at the "long end" of the Treasury yield curve.

3.2 Permanent Open Market Operations

We use a database of all permanent (outright) open market operations (POMOs) executed by the Federal Reserve Bank of New York (FRBNY) between January 2, 2001 and December 31, 2007. As discussed in Section 2.2, the Desk at the FRBNY trades Treasury securities on behalf of the Federal Reserve System in response to perceived persistent deviations of the aggregate level of nonborrowed reserves in the monetary system from a non-public target consistent with the publicly known target level of the federal funds rate.

POMOs are executed by the Desk through an auction with primary dealers usually taking place between 10:00 a.m. and 11:30 a.m. ET (Akhtar, 1997; Harvey and Huang, 2002; D'Amico and King, 2010), i.e., when intraday market liquidity is relatively high (Fleming, 1997; Mizrach and Fleming, 2009). This process is made of multiple steps. Around 10:00 a.m., the Desk announces a list of eligible Treasury securities (i.e., of CUSIPs) for the auction. This list typically includes all securities within a specific maturity segment targeted by the Desk, with the exception of the *cheapest-to-deliver* in the futures market and any highly scarce (i.e., *on special*) security in the repo market. Market participants do not learn about the total amounts auctioned and the individual securities of interest to the FRBNY until the daily auction list is announced. The auction closes between 11 a.m. and 11:30 a.m. Within a few minutes afterwards, the Desk selects among the submitted bids using a proprietary algorithm and publishes the auction results. Following these trades, the reserve accounts of the Desk's counterparties (the dealers' banks) at the FRBNY are credited or debited accordingly, thus permanently altering the aggregate supply of nonborrowed reserves in the monetary system.[34]

[34] Importantly, the POMOs in our dataset do not include those circumstances in which the FRBNY replaces maturing securities in its portfolio by rolling (usually) all or (occasionally) some of them over at Treasury auctions to prevent undesired reserve drains. According to Akhtar (1997, p. 37), the "Federal Reserve is prohibited by law from adding to its net position by direct purchases of securities from the Treasury — that is, the Federal Reserve has no authority for direct lending to the Treasury. As a consequence, at most the Desk's acquisition at Treasury auctions can equal maturing holdings."

Our database contains salient information on the Desk's POMOs: Their dates, actual securities traded (CUSIPs), descriptions (coupon rate and maturity), and par amounts accepted at the auction. In order to capture the Desk's stated focus on broad maturity segments (rather than on specific securities), we group all auctioned securities based on their remaining maturity into five brackets centered around the maturities of the on-the-run securities available in the BrokerTec database: Two-year, three-year, five-year, ten-year, and thirty-year POMOs.[35] The scarce liquidity of most off-the-run issues precludes a security-level analysis of price formation in the presence of POMOs. Our inference is likely only weakened by this aggregation, and is robust to alternative bracket definitions.

Table 2 contains summary statistics of POMOs for each maturity bracket, as well as for every intervention day (labeled Total), over three partitions of our sample: 2001-2007 (Panel A), 2001-2004 (Panel B), and 2005-2007 (Panel C). The FRBNY's Desk executed POMOs in 217 days between 2001 and 2007. When doing so, the Desk traded an average of about 28 different securities on any single day in which it intervened. As mentioned above, this suggests that POMOs do not target (nor appear to significantly affect the supply of) any particular security within a maturity bracket. POMOs occur most frequently at the shortest, most liquid segments of the yield curve, the two-year to five-year maturities. As Table 2 shows, occasionally the Desk trades securities in more than one maturity bracket. Daily total par amounts accepted ($POMO_{i,t}$) average between \$343 million for ten-year bonds and \$1.152 billion for three-year notes. While sizeable, these amounts are significantly lower than sample average daily trading volume not only in the whole secondary U.S. Treasury market (\$469 billion)[36] but also in the on-the-run Treasury securities in our dataset (see $V_{i,t}$ in Table 1). Figure 3 plots the daily total par amount of the FRBNY's POMOs ($POMO_t$, solid column), the end-of-day federal funds rate (dotted line), and the corresponding target rate set by the FOMC (solid line) over our sample period. POMOs appear to cluster in time — especially during the earlier, less liquid, and more volatile interval 2001-2004 (see Panel B of Tables 1 and 2) — yet still occur in every year of the sample. Interestingly, the Desk executed exclusively purchases ($POMO_t$, $POMO_{i,t} > 0$) between

[35] Specifically, as in D'Amico and King (2010), we label a FRBNY transaction as *i)* a two-year POMO if the remaining maturity of the traded security is between zero and four years; *ii)* a three-year POMO if the remaining maturity of the traded security is between one and five years; *iii)* a five-year POMO if the remaining maturity of the traded security is between three and seven years; *iv)* a ten-year POMO if the remaining maturity of the traded security is between eight and twelve years; and *v)* a thirty-year POMO if the remaining maturity of the traded security is greater than twelve years. Some brackets are partially overlapping because of the high substitutability of some bonds across maturities. The inference that follows is unaffected by employing non-overlapping brackets.

[36] This average is computed from trading volume data reported by primary dealers to the FRBNY and available at http://www.newyorkfed.org/markets/gsds/search.cfm.

2001 and 2007, regardless of the interest rate environment, both in aggregate (Figure 3) and in each of the maturity brackets (Table 2). This may reflect the Desk's efforts to accommodate the persistent growth in the demand for U.S. money over the sample period (mirroring the growth in the economy) by expanding the supply of nonborrowed reserves (Akhtar, 1997).[37]

4 Empirical Analysis

The model of Section 2 generates several implications for the impact of POMOs on the process of price formation in the secondary market for U.S. Treasury securities. In this section we assess the empirical relevance of our model within the comprehensive sample of that market described in Section 3. We proceed in two steps. First, we test the main equilibrium implication of our model, i.e., that outright interventions by the FRBNY improve equilibrium market liquidity. Second, we assess whether this effect can be attributed to the informational role of trading, as uniquely postulated by our model.

4.1 POMOs and Market Liquidity

The main prediction of our stylized model is that outright trades by the FRBNY (POMOs) lower the equilibrium price impact of order flow ($\Delta\lambda \equiv \lambda_{CB} - \lambda < 0$, Remark 1). Intuitively, this outcome stems from uninformative POMOs alleviating adverse selection risk for the MMs. As discussed in Section 3.1.1, in this paper we capture a Treasury security's daily market liquidity with that security's average daily bid-ask price spread, $S_{i,t}$. Accordingly, our model predicts a *tighter* bid-ask spread (i.e., a lower $S_{i,t}$) for the targeted maturity bracket in days when POMOs occur.

To test this prediction, we define liquidity changes on any POMO day as $\Delta S^B_{i,t} \equiv S_{i,t} - S^B_{i,t}$, the difference between the average bid-ask price spread on the day a POMO occurred, $S_{i,t}$, and a benchmark pre-intervention level, $S^B_{i,t}$. Because POMOs often cluster in time (e.g., see Figure 3), we do not compare $S_{i,t}$ to the average bid-ask price spread on the day before a POMO occurred (i.e., $S^B_{i,t} = S_{i,t-1}$). Instead, we compute $S^B_{i,t}$ as the average bid-ask price spread over the most recent previous 22 trading days when no POMO occurred (e.g., Pasquariello, 2007b). Alternative intervals lead to similar inference. Consistent with the trend for $S_{i,t}$ displayed in Figure 2, so-

[37] Accordingly, the website of the FRBNY (http://www.newyorkfed.org/markets/pomo_landing.html) observes that "[t]raditionally, [outright] purchases of Treasury securities for the [System Open Market Account] were conducted to offset factors that permanently drain balances from the banking system, including U.S. currency in circulation, among other factors."

defined daily spread changes are also on average negative over our sample period (see Table 1). We then compute averages of these differences for each on-the-run Treasury note and bond in our BrokerTec sample *i)* over days when POMOs occurred in the corresponding maturity bracket (i.e., when the event dummy $I_{i,t}^{CB} = 1$); as well as *ii)* over days when *any* POMO occurred (i.e., when the event dummy $I_t^{CB} = 1$). The latter effects may stem from the relatively high substitutability of on-the-run Treasury securities (e.g., Cohen, 1999; D'Amico and King, 2010; Greenwood and Vayanos, 2010).[38] We report these averages, labeled $\overline{\Delta S_{i,t}^B}$, in Table 3.[39]

Consistent with our model, mean daily bid-ask spreads *decline* on both *same-maturity* and *any-maturity* POMO days. These *univariate* tests may have low power because of the relative paucity of POMO days over our sample period (see Table 2). Nevertheless, estimates for $\overline{\Delta S_{i,t}^B}$ in Table 3 are always negative, much larger than their sample-wide means (in Table 1), and both statistically and economically significant at most maturities. For instance, total roundtrip costs per daily trading volume in benchmark five-year Treasury notes ($V_{i,t}$, in Table 1) decline on average by more than \$400,000 ($\overline{\Delta S_{i,t}^B} = (-0.240/10,000) \times \$17.6$ billion) — i.e., by nearly 42% of the sample-wide standard deviation of $\Delta S_{i,t}^B$ (0.580, in Table 1) — on days when the Desk is trading these securities. Table 3 also provides strong evidence of liquidity spillovers in correspondence with any outright trade by the FRBNY: $\overline{\Delta S_{i,t}^B} < 0$ for all maturities, regardless of the segment of the yield curve targeted by the Desk, and by 7% to 16% of their mean bid-ask spreads ($S_{i,t}$, in Table 1). As discussed in Section 3.2, these estimates are obtained from on-the-run Treasury securities in the targeted segments, rather than from the actual securities being traded by the Desk, because of the often scarce liquidity of the latter. Thus, they are likely to underestimate the true extent of the impact of POMOs on Treasury market liquidity.

Improvements in Treasury market liquidity in proximity of POMOs may be due to changes in bond characteristics and calendar effects unrelated to FRBNY interventions. For instance, changes in Treasury securities' sensitivity to yield dynamics (as proxied by modified duration, $D_{i,t}$, and convexity, $C_{i,t}$) may affect their perceived riskiness to dealers and investors (e.g., Strebulaev, 2002; Goldreich et al., 2005; Pasquariello and Vega, 2009). Bid-ask spreads and trading activity also display weekly seasonality and time trends (e.g., Fleming, 1997, 2003; Pasquariello and Vega, 2007). In particular, bid-ask spreads on the BrokerTec platform have considerably tightened — and trading volume has likewise increased — over our sample period, especially

[38]Spillover of the positive liquidity externalities of government intervention described in Remark 1 across highly substitutable assets would likely occur in any model of multi-asset trading in which adverse selection considerations affect equilibrium market liquidity (e.g., see Pasquariello, 2007a, and references therein).

[39]The occasional gaps in BrokerTec coverage and the quote filtering procedures described in Section 3.1 result in a loss of some event days in the merged BrokerTec/POMO sample, especially for three-year notes.

from 2005 onward. These effects may either enhance or obfuscate the impact of POMOs on the process of price formation in the Treasury bond market. We assess the robustness of our univariate inference to these considerations by specifying the following *multivariate* model of bid-ask price spread changes for both same-maturity ($I_{i,t}^{CB} = 1$) and any-maturity POMOs ($I_t^{CB} = 1$):

$$\Delta S_{i,t}^{B} = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^{B} + \alpha_{i,\Delta C} \Delta C_{i,t}^{B} + \alpha_{i,CB} I_{i,t}^{CB} + \varepsilon_{i,t}, \qquad (8)$$

where $\Delta S_{i,t}^{B}$ is computed over every day of our sample, $Calendar_t$ is a vector of day-of-the-week, month, and year dummies, $\Delta D_{i,t}^{B} \equiv D_{i,t} - D_{i,t}^{B}$, $\Delta C_{i,t}^{B} \equiv C_{i,t} - C_{i,t}^{B}$, and $D_{i,t}^{B}$ and $C_{i,t}^{B}$ are average modified duration and convexity over the most recent previous 22 trading days when no POMO occurred, respectively. Eq. (8) allows us to compare bid-ask price spread changes on POMO days to such changes in *every other* trading day over our sample period — rather than among POMO days *alone*, as in the univariate tests for $\overline{\Delta S_{i,t}^{B}}$. The inclusion of calendar fixed effects and bond characteristics in Eq. (8) only weakens our inference.[40]

We estimate these regressions for each on-the-run maturity in our database separately by Ordinary Least Squares (OLS). We evaluate the statistical significance of the coefficients' estimates, reported in Table 3, with Newey-West standard errors to correct for heteroskedasticity and serial correlation. The results in Table 3 provide further, strong support for our model's main prediction. Consistent with the prior univariate evidence, bid-ask spreads tend to decline (i.e., $\alpha_{i,CB} < 0$ in Eq. (8)) both when same-maturity and any-maturity POMOs occur. This decline is often both statistically and economically significant — e.g., amounting on average to more than 8% (27%) of the corresponding sample mean spread (standard deviation of spread change) in Table 1 — with the exception of three-year notes, whose coverage in our sample is less than complete.

We also consider whether our inference may be attributed to sample-specific issues. As discussed in Section 3.1, bid-ask spreads are much wider (and more volatile) during the earlier portion of our sample, 2001-2004. That period encompasses both significant economic and financial uncertainty — e.g., the bursting of the Internet bubble, the events of 9/11, the short NBER recession in the Fall of 2001, and the accompanying changes in the Federal Reserve's monetary policy (see Figure 3) — as well as the migration of most trading in on-the-run Treasury securities from the voice-brokered GovPX platform to two electronic platforms — BrokerTec and eSpeed. We assess the effect of these circumstances on our inference in two ways. First, we estimate both $\overline{\Delta S_{i,t}^{B}}$ and $\alpha_{i,CB}$ separately within either the earlier, high-spread subsample (2001-2004, in Panel

[40]The time series $S_{i,t}$ are made of several different on-the-run securities *stacked* on each other over the sample period (as in Brandt and Kavajecz, 2004; Green, 2004; Pasquariello and Vega, 2007, 2009). Unreported analysis shows our inference to be insensitive to the inclusion of security fixed effects in Eq. (8).

A of Table 4) or the later, low-spread one (2005-2007, in Panel B of Table 4). According to our model, the worse is market liquidity the greater is its improvement in correspondence with uninformative government interventions, for the more severe adverse selection risk may have been in their absence (e.g., see Section 2.3). Consistently, Table 4 indicates that much of the decline in bid-ask spreads described above is concentrated in the earlier (low-liquidity) subsample, less so in the later (high-liquidity) one. Thus, this evidence provides further support for our model.[41] Second, we extend our analysis to all available GovPX data within our sample period. This data includes price midquotes and bid-ask spreads for two-year, three-year, five-year, and ten-year notes between 2001 and 2004. Voice-brokered trading in on-the-run securities virtually ceases afterward. We then estimate both $\overline{\Delta S_{i,t}^{B}}$ and $\alpha_{i,CB}$ within this dataset. These estimates (in Panel C of Table 4) are similar in sign, magnitude, and significance to those from our BrokerTec sample. This suggests that our inference cannot be attributed to the gradual migration of trading activity in on-the-run Treasury securities from GovPX to BrokerTec.

The estimated improvement in Treasury market liquidity accompanying POMOs is unlikely to stem from inventory considerations. The role of inventory management is often invoked in the literature (surveyed in the Introduction) studying Central Bank interventions in currency markets. According to these studies, government interventions, regardless of their information content, may hinder dealers' ability to provide liquidity to other market participants — e.g., because of inventory targets, stringent capital constraints, "hot potato" effects, or limited risk-bearing capacity. This may ultimately lead to *wider* bid-ask spreads, contrary to the evidence in Tables 3 and 4.[42] Inventory considerations may also lead to asymmetric supply effects of POMOs on market liquidity. For instance, the Desk's outright sales (purchases) of notes and bonds — $POMO_{i,t} > 0$ ($POMO_{i,t} < 0$) — may decrease (increase) on-the-run bid-ask spreads by lowering (magnifying) dealers' search costs for sought-after Treasury securities (e.g., Vayanos and Weill, 2008; D'Amico and King, 2010). However, the Desk not only did not sell any Treasury security over our sample period, but also explicitly avoids trading in what the market perceives as "scarce" securities (see Section 3.2).

Alternatively, POMOs may affect liquidity provision in the Treasury bond market by altering reserve market conditions for participating dealers with depository facilities, even if those

[41] We explore in greater detail the role of fundamental uncertainty for our inference in Section 4.2.3.

[42] In a sequential model of trading, Pasquariello (2010) shows that the mere likelihood (yet not the actual occurrence) of large government intervention may induce competitive dealers to tighten their posted bid-ask spreads to pass all rents from trading with the Central Bank onto investors, if faced with a prior large imbalance between buyers and sellers of the traded asset. These circumstances are unlikely to have arisen repeatedly and concurrently over our sample period.

trades had no discernible impact on the informational role of trading in that market (as instead postulated by our model).[43] For example, POMO purchases (sales) may ease (tighten) market-makers' liquidity provision by increasing (decreasing) the availability of credit and capital — i.e., dealers' funding liquidity — ultimately leading to tighter (wider) bid-ask spreads in the Treasury market (e.g., Brunnermeier and Pedersen, 2009). This channel is likely to play a prominent role in correspondence with significant episodes of market turmoil, when credit and capital may be scarce. Yet, this is unlikely to have been the case over our sample period 2001-2007. By design, our sample ends prior to the financial crisis following the collapse of Bear Sterns and Lehman Brothers in 2008. As such, it does not include the accompanying extraordinary trading activity by the FRBNY in the Treasury market — e.g., a few large sales in the Spring of 2008 and several sizable purchases afterwards — discussed in Section 3.1. Unreported evidence shows that *i)* our inference is either unaffected or only weakened by the inclusion of the crisis period January 2008-March 2009;[44] *ii) both* POMO purchases and sales during this crisis period are accompanied on average by *tighter* bid-ask spreads, especially within the ninety-minute intraday interval surrounding POMO auctions (see Sections 3.1 and 3.2); and *iii)* F-tests nearly always fail to reject the null hypothesis that estimated average (daily or intraday) bid-ask spread changes on (same-maturity or any-maturity) POMO days during this crisis period are the *same* for both FRBNY purchases and sales. We conclude that Treasury market liquidity improves in the wake of their occurrence regardless of their impact on dealers' inventories, on the relative supply of the traded securities, or on reserve market conditions for liquidity providers.

4.2 POMOs and the Informational Role of Trading

The evidence in Tables 3 and 4 provides strong support for our model's main implication: POMOs executed by the FRBNY's Desk in the secondary market for Treasury securities meaningfully *improve* Treasury market liquidity — i.e., on average lowering daily bid-ask price spreads across all segments of the yield curve — especially when such liquidity is lower. As discussed in Section 4.1, this effect is unlikely to be systematically explained by inventory management or liquidity provision considerations. Our model attributes these effects to the impact of government intervention on the Treasury market's information environment. In this section, we assess more directly this

[43]For instance, Brunetti et al. (2011) report that TOMOs by the European Central Bank generally improve the liquidity of the e-MID, the electronic interbank market for Euro-denominated unsecured deposits and loans.

[44]Specifically, we augment our sample with bond and intervention data between January 1, 2008 and March 24, 2009, i.e., until the last trading day before the FRBNY began executing its LSAP policy described in Section 3.1. Consistently, Brunetti et al. (2011) find that TOMOs by the European Central Bank either fail to improve or worsen the liquidity of the interbank Euro deposit market during the aforementioned crisis period.

basic, novel premise of our theory by testing its unique predictions for market liquidity (also in Remark 1) stemming from the informational role of trading in that market.

4.2.1 Information Heterogeneity

The first prediction from Remark 1 states that, ceteris paribus, greater information heterogeneity among speculators (i.e., lower ρ) magnifies the positive liquidity externalities of government intervention (i.e., a more negative $\Delta\lambda$, as in Figure 1c). Intuitively, more heterogeneously informed speculators trade more cautiously to protect their perceived private information monopoly. The ensuing greater adverse selection risk for the MMs worsens market liquidity, i.e., increases the equilibrium price impact of aggregate order flow. In those circumstances, Central Bank trades attempting to achieve its non-public, uninformative policy target more significantly mitigate the more severe threat of adverse selection in market-making.

Testing for this prediction requires measurement of ρ, the heterogeneity of private information about fundamentals among sophisticated Treasury market participants. Marketwide information heterogeneity is commonly proxied by the standard deviation across professional forecasts of economic variables (e.g., Diether et al., 2002; Green, 2004; Pasquariello and Vega, 2007, 2009; Kallberg and Pasquariello, 2008; Yu, 2011). To that purpose, we obtain the quarterly analyst forecasts of U.S. macroeconomic announcements collected by the Federal Reserve Bank of Philadelphia in its Survey of Professional Forecasters (SPF). The SPF, initiated in 1968 by the American Statistical Association and the National Bureau of Economic Research, is the only such survey continuously available over our sample period, and is commonly used in empirical research on the formation of macroeconomic expectations.[45] For each quarter q, the SPF database contains individual analyst forecasts for several macroeconomic announcements and at several future horizons. We focus on next-quarter forecasts for arguably the most important of them: Unemployment, Non Farm Payroll, Nominal GDP, CPI, Industrial Production, and Housing Starts (e.g., Pasquariello and Vega, 2007; Brenner et al., 2009). We define the dispersion of beliefs among speculators for each macroeconomic variable p in quarter q as the standard deviation of its forecasts in that quarter, $SDF_{p,q}$. We then compute the aggregate degree of information heterogeneity about macroeconomic fundamentals in quarter q, $SSDF_q$, as a simple average of all standardized forecast dispersions in that quarters (see Figure 4a).[46]

[45] Croushore (1993) provides a detailed description of the SPF database. An equally popular survey of professional forecasts of U.S. macroeconomic announcements administered by the International Money Market Services Inc. (MMS) has been discontinued in 2003.

[46] Normalization is necessary because units of measurement differ across macroeconomic variables. We also shift the mean of $SSDF_q$ by a factor of five to ensure that $SSDF_q$ is always positive. Importantly, $SSDF_q$ and the

As in Section 4.1, we assess the impact of marketwide information heterogeneity on POMOs' positive liquidity externalities via two parsimonious empirical strategies. First, we estimate the slope coefficients of univariate regressions of average bid-ask spread changes ($\Delta S_{i,t}^{B}$) over (same-maturity or any-maturity) POMO days *alone* ($I_{i,t}^{CB}=1$ or $I_{t}^{CB}=1$) on the contemporaneous realizations of $SSDF_{q}$. For ease of interpretation, we then use the resulting OLS estimates ($a_{i,CB}^{x}$) to compute differences (in bps) between $\Delta S_{i,t}^{B}$ in POMO days during quarters when marketwide information heterogeneity was either *historically high* (low ρ) — i.e., for $SSDF_{q}\geq SSDF_{q}^{70^{th}}$, the top 70th percentile of its empirical distribution — or historically *low* (high ρ) — i.e., for $SSDF_{q}\leq SSDF_{q}^{30^{th}}$, the bottom 30th percentile of its empirical distribution. We report these differences in Table 5, labeled as $\overline{\Delta\Delta S_{i,t}^{B,x}}=a_{i,CB}^{x}\left(X_{t}^{70^{th}}-X_{t}^{30^{th}}\right)$for $X_{t}=SSDF_{q}$.

Second, we amend the multivariate regression models of Eq. (8) to include the cross-products of same-maturity and any-maturity POMO dummies ($I_{i,t}^{CB}$ and I_{t}^{CB}), as follows:

$$\Delta S_{i,t}^{B}=\alpha_{i,0}+\alpha_{i,C}Calendar_{t}+\alpha_{i,\Delta D}\Delta D_{i,t}^{B}+\alpha_{i,\Delta C}\Delta C_{i,t}^{B}+\alpha_{i,CB}I_{i,t}^{CB}+\alpha_{i,CB}^{x}I_{i,t}^{CB}X_{t}+\varepsilon_{i,t},\quad(9)$$

where $X_{t}=SSDF_{q}$. Eq. (9) attempts to capture any state dependency (from X_{t}) in bid-ask spread changes on POMO days with respect to changes over the *whole* sample period, while accounting for calendar effects, time-varying changes in important bond characteristics, and time trends in X_{t}.[47] As above, we compute differences (in bps) between OLS estimates of the impact of POMOs on bid-ask spread changes in days characterized by historically high information heterogeneity — i.e., for $X_{t}^{70^{th}}=SSDF_{q}^{70^{th}}$ — and those same estimates in days characterized by historically low information heterogeneity — i.e., for $X_{t}^{30^{th}}=SSDF_{q}^{30^{th}}$. We report these differences in Table 5, labeled as $\Delta\alpha_{i,CB}^{x}=\alpha_{i,CB}^{x}\left(X_{t}^{70^{th}}-X_{t}^{30^{th}}\right)$ for $X_{t}=SSDF_{q}$.[48]

Consistent with Remark 1, estimated spread change differentials are most often *negative* and statistically significant — i.e., $\overline{\Delta\Delta S_{i,t}^{B,x}}<0$ and $\Delta\alpha_{i,CB}^{x}<0$ — in correspondence with both same-

other information proxies described below are virtually uncorrelated.

[47]Eq. (9) does not allow for X_{t} to affect $\Delta S_{i,t}^{B}\equiv S_{i,t}-S_{i,t}^{B}$ on non-POMO days. According to our basic model (see Proposition 1, in Section 2.1) and extant empirical evidence (e.g., Pasquariello and Vega, 2007), the information environment of the U.S. Treasury market (e.g., information heterogeneity ρ or fundamental volatility σ_{v}^{2}) may affect its equilibrium liquidity (λ of Eq. (3)) even in absence of Central Bank interventions. However, our low-frequency information measures X_{t} are likely to impact both $S_{i,t}$ and $S_{i,t}^{B}$; thus, the effects of those measures on market liquidity are likely to cancel out in $\Delta S_{i,t}^{B}$. Consistently, unreported analysis reveals $\Delta S_{i,t}^{B}$ to be largely insensitive to our proxies X_{t} and our inference to be unaffected by their inclusion in Eq. (9).

[48]In this section we only report and discuss means and regression coefficients estimated over the full BrokerTec sample period 2001-2007. As Figure 4 illustrates, neither $SSDF_{q}$ nor the additional information proxies defined below display enough variation over either of the two subperiods 2001-2004 and 2005-2007 analyzed in Section 4.1. Nevertheless, this additional evidence (available on request) broadly confirms our inference, especially in the earlier, low-liquidity subsample (as our model implies).

maturity ($I_{i,t}^{CB} = 1$) and any-maturity POMOs ($I_t^{CB} = 1$), for both on-the-run Treasury notes and bonds. For instance, Table 5 shows that on average, bid-ask spreads for two-year, five-year, and ten-year Treasury notes on any-maturity POMO days when our proxy for marketwide dispersion of beliefs $SSDF_q$ is high decline by roughly 106% (of the baseline effect in Table 3) more — or about 0.184 bps more — than when $SSDF_q$ is low (i.e., mean significant $\Delta\alpha_{i,CB}^x/\alpha_{i,CB} = 1.06$). Table 5 further indicates that, in correspondence with government intervention at the long-end of the yield curve, bid-ask spreads for thirty-year Treasury bonds when $SSDF_q$ is high are no less than 1.5 bps lower than when $SSDF_q$ is low (i.e., $\overline{\Delta\Delta S_{i,t}^{B,x}} = -1.550$ and $\Delta\alpha_{i,CB}^x = -1.589$). This evidence suggests that government interventions have a greater impact on the process of price formation in the secondary market for Treasury securities when information heterogeneity among speculators is high, as postulated by our model.

4.2.2 Fundamental Uncertainty

The second prediction from Remark 1 states that, ceteris paribus, greater uncertainty about the traded asset's payoff (i.e., higher σ_v^2) amplifies the impact of government intervention on market liquidity — i.e., leads to higher $|\Delta\lambda|$ (Figure 1d). Greater fundamental uncertainty worsens equilibrium market liquidity, for it makes speculators' private information more valuable and the accompanying adverse selection risk for the MMs more severe. As discussed above, this enhances the positive liquidity externalities of Central Bank trades.

To evaluate this implication of our model, we proxy for σ_v^2 with $EURVOL_m$ (plotted in Figure 4b), the monthly average (to smooth daily variability) of daily Eurodollar implied volatility from Bloomberg. $EURVOL_m$ is commonly used as a measure of market participants' perceived uncertainty surrounding U.S. macroeconomic fundamentals (e.g., Pasquariello and Vega, 2009). We then run the univariate and multivariate tests for spread change differentials described in Section 4.2.1 — by estimating $\overline{\Delta\Delta S_{i,t}^{B,x}}$ for the former and $\Delta\alpha_{i,CB}^x$ for the latter — after imposing that $X_t = EURVOL_m$. We report these estimates in Table 6.

Consistent with Remark 1, both $\overline{\Delta\Delta S_{i,t}^{B,x}}$ and $\Delta\alpha_{i,CB}^x$ are always *negative*, but are statistically significant only at the mid–section of the yield curve. In those circumstances, bid-ask spreads tighten much more pronouncedly on POMO days characterized by higher fundamental uncertainty — e.g., by no less than 100% of the baseline decline in spread reported in Table 3. For example, Table 6 shows that during same-maturity POMO days when $SSDF_q$ is historically high, the bid-ask spreads for ten-year Treasury notes decline by 0.318 bps more ($\Delta\alpha_{i,CB}^x = -0.318$) than when $SSDF_q$ is low. This effect is economically significant, for it amounts to roughly 35% of the sample-wide standard deviation of $\Delta S_{i,t}^B$ in Table 1. This evidence suggests that government interventions are accompanied by a greater improvement in Treasury market liquidity when fundamental uncertainty is higher, as implied by our model.

4.2.3 POMO Policy Uncertainty

The last prediction from Remark 1 states that, ceteris paribus, greater uncertainty about the Central Bank's uninformative policy target p_T among market participants (i.e., higher σ_T^2) enhances the improvement in equilibrium market liquidity accompanying its trades ($\Delta\lambda$, as in Figure 1b). Greater policy uncertainty complicates the MMs' attempt at accounting for the extent of uninformative government intervention in the aggregate order flow before setting the equilibrium price p_1. Yet, it also lowers their perceived adverse selection risk from trading with privately informed speculators.

As discussed in Sections 2.2 and 3.2, the FRBNY's Desk targets the aggregate level of nonborrowed reserves available in the banking system via uninformative POMOs to ensure that conditions in the federal funds rate market are "consistent" with the public and informative target rate set by the FOMC.[49] Thus, uncertainty among market participants about the FRBNY's non-public and uninformative reserve target for POMOs may manifest itself in the federal funds market. Accordingly, we measure marketwide policy uncertainty surrounding the Desk's POMOs with $FEDVOL_m$ (plotted in Figure 4c), the monthly average (to smooth daily variability) of daily standard deviation of the federal funds rate, from the FRBNY.[50] We then assess the sensitivity of spread changes in correspondence with POMOs to $FEDVOL_m$ by means of the univariate and multivariate tests of Section 4.2.1.

Both sets of tests, in Table 7, provide further support for our model. As postulated by Remark 1, once again $\overline{\Delta\Delta S_{i,t}^{B,x}} < 0$ and $\Delta\alpha_{i,CB}^{x} < 0$ for most maturities and in correspondence with both same-maturity ($I_{i,t}^{CB} = 1$) and any-maturity POMOs ($I_{t}^{CB} = 1$). Hence, these estimates suggest that liquidity improves more pronouncedly on POMO days when uncertainty about the Desk's policy (proxied by $FEDVOL_m$) is historically high. This effect is especially strong for thirty-year Treasury bonds, whose bid-ask price spreads on same-maturity POMO days when $FEDVOL_m$ is large (i.e., at or above the 70^{th} percentile of its empirical distribution) are about 1.8 bps (or 22% of its sample mean in Table 1) lower than when $FEDVOL_m$ is small (i.e., at or below the 30^{th} percentile of its empirical distribution). Table 7 also shows that, when negative and statistically

[49] For example, the website of the FRBNY (http://www.newyorkfed.org/markets/pomo_landing.html) states that "[p]urchases or sales of Treasury securities on an outright basis have been used historically to manage the supply of reserves in the banking system [...] to maintain conditions in the market for bank reserves consistent with the federal funds target rate set by the [FOMC]."

[50] This data is available at http://www.newyorkfed.org/markets/omo/dmm/fedfundsdata.cfm.

significant, the estimated cross-product coefficients $\Delta\alpha^{x}_{i,CB}$ for all other maturities are between 29% and 65% higher than the baseline estimated bid-ask spread decline $\alpha_{i,CB}$ (from Eq. (8)) in Table 3.

In short, the evidence in Tables 5 to 7 indicates that the informational role of trading importantly affects the impact of government interventions on the process of price formation in the secondary market for Treasury securities, as predicated by our model.

5 Conclusions

The many severe episodes of financial turmoil affecting the global economy in the past decade have led to increasing calls for greater, more direct involvement of governments and monetary authorities in the process of price formation in financial markets. The objective of this study is to shed light on the implications of this involvement for financial market quality.

To that purpose, we investigate the impact of permanent open market operations (POMOs) by the Federal Reserve Bank of New York (FRBNY) — on behalf of the Federal Reserve System — on the microstructure of the secondary U.S. Treasury bond market. POMOs are outright trades in previously issued U.S. Treasury securities (i.e., permanently affecting the supply of nonborrowed reserves in the banking system) to accomplish a non-public, uninformative reserve target consistent with the federal funds target rate set by the Federal Open Market Committee (FOMC). To guide our analysis, we construct a model of trading in the Treasury market in which — consistent with much recent empirical evidence (e.g., Brand and Kavajecz, 2004; Green, 2004; Pasquariello and Vega, 2007, 2009) — the presence of strategic, heterogeneously informed speculators enhances adverse selection risk for uninformed market-makers (MMs). In this basic setting, we introduce a stylized Central Bank facing a trade-off between a non-public, uninformative policy goal and its expected cost. The main novel insight of our model is twofold. First, the Central Bank's trading activity improves equilibrium market liquidity because it alleviates MMs' adverse selection concerns when facing the aggregate order flow (thanks to the uninformativeness of its non-public target). Second, the extent of this improvement is sensitive to the informational role of trading.

Our subsequent empirical analysis of a comprehensive sample of price formation and FRBNY trades in the secondary U.S. Treasury market between 2001 and 2007 provides strong, robust support for these insights. Our evidence shows that *i)* bid-ask spreads for on-the-run Treasury notes and bonds decline on days when the FRBNY executes POMOs; and *ii)* the estimated magnitude of this decline on POMO days is greater when Treasury market liquidity is lower, as well as increasing in measures of volatility of U.S. economic fundamentals, marketwide dispersion of beliefs about them, and uncertainty about the FRBNY's POMO policy, as implied by our model.

Overall, these findings indicate that the externalities of government intervention in financial markets for their process of price formation may be economically and statistically significant, as well as crucially related to the targeted markets' information environment. We believe these are important contributions to current and future research on official trading activity and market manipulation.

6 Appendix

Proof of Proposition 1. The proof is by construction: We first conjecture general linear functions for the pricing rule and speculators' demands; we then solve for their parameters satisfying Conditions 1 and 2; finally, we show that these parameters and functions represent a rational expectations equilibrium. We start by guessing that equilibrium p_1 and $x(m)$ are given by $p_1 = A_0 + A_1\omega_1$ and $x(m) = B_0 + B_1\delta_v(m)$, respectively, where $A_1 > 0$. Those expressions and the definition of ω_1 imply that, for each speculator m,

$$E[p_1|\delta_v(m)] = A_0 + A_1 x(m) + A_1 B_0 (M-1) + A_1 B_1 (M-1)\rho\delta_v(m). \tag{A-1}$$

Using Eq. (A-1), the first order condition of the maximization of each speculator m's expected profit $E[\pi(m)|\delta_v(m)]$ with respect to $x(m)$ is given by

$$p_0 + \delta_v(m) - A_0 - (M+1)A_1B_0 - 2A_1B_1\delta_v(m) - (M-1)A_1B_1\rho\delta_v(m) = 0. \tag{A-2}$$

The second order condition is satisfied, since $2A_1 > 0$. For Eq. (A-2) to be true, it must be that

$$p_0 - A_0 = (M+1)A_1B_0 \tag{A-3}$$

$$2A_1B_1 = 1 - (M-1)A_1B_1\rho. \tag{A-4}$$

The distributional assumptions of Section 2.1 imply that the order flow ω_1 is normally distributed with mean $E(\omega_1) = MB_0$ and variance $var(\omega_1) = MB_1^2\rho\sigma_v^2[1+(M-1)\rho] + \sigma_z^2$. Since $cov(v,\omega_1) = MB_1\rho\sigma_v^2$, it ensues that

$$E(v|\omega_1) = p_0 + \frac{MB_1\rho\sigma_v^2}{MB_1^2\rho\sigma_v^2[1+(M-1)\rho]+\sigma_z^2}(\omega_1 - MB_0). \tag{A-5}$$

According to the definition of a Bayesian-Nash equilibrium in this economy (Section 2.1), $p_1 = E(v|\omega_1)$. Therefore, our conjecture for p_1 yields

$$A_0 = p_0 - MA_1B_0 \tag{A-6}$$
$$A_1 = \frac{MB_1\rho\sigma_v^2}{MB_1^2\rho\sigma_v^2\left[1+(M-1)\rho\right]+\sigma_z^2}. \tag{A-7}$$

The expressions for A_0, A_1, B_0, and B_1 in Proposition 1 must solve the system made of Eqs. (A-3), (A-4), (A-6), and (A-7) to represent a linear equilibrium. Defining A_1B_0 from Eq. (A-3) and plugging it into Eq. (A-6) leads us to $A_0 = p_0$. Thus, it must be that $B_0 = 0$ to satisfy Eq. (A-3). We are left with the task of finding A_1 and B_1. Solving Eq. (A-4) for A_1, we get

$$A_1 = \frac{1}{B_1\left[2+(M-1)\rho\right]}. \tag{A-8}$$

It then follows from equating Eq. (A-8) to Eq. (A-7) that $B_1^2 = \frac{\sigma_z^2}{M\rho\sigma_v^2}$, i.e. that $B_1 = \frac{\sigma_z}{\sqrt{M\rho}\sigma_v}$. Substituting this expression back into Eq. (A-8) implies that $A_1 = \frac{\sigma_v\sqrt{M\rho}}{\sigma_z[2+(M-1)\rho]}$. Finally, we observe that Proposition 1 is equivalent to a symmetric Cournot equilibrium with M speculators. Therefore, the "backward reaction mapping" introduced by Novshek (1984) to find n-firm Cournot equilibria proves that, given any linear pricing rule, the symmetric linear strategies $x(m)$ of Eq. (2) indeed represent the unique Bayesian Nash equilibrium of the Bayesian game among speculators. ■

Proof of Corollary 1. The first part of the statement stems from the fact that $\frac{\partial\lambda}{\partial\sigma_v} = \frac{\sqrt{M\rho}}{\sigma_z[2+(M-1)\rho]} > 0$. Furthermore, $\frac{\partial\lambda}{\partial\rho} = -\frac{\sigma_v M[(M-1)\rho-2]}{2\sigma_z\sqrt{M\rho}[2+(M-1)\rho]^2} < 0$ except in the small region of $\{M, \rho\}$ where $\rho \leq \frac{2}{M-1}$. ■

Proof of Proposition 2. The outline of the proof is similar to the one of the proof of Proposition 1. We begin by conjecturing the following functional forms for the equilibrium price and trading activity of speculators and the Central Bank: $p_1 = A_0 + A_1\omega_1$, $x(m) = B_0 + B_1\delta_v(m)$, and $x_{CB} = C_0 + C_1\delta_{CB} + C_2\delta_T$, respectively, where $A_1 > 0$. Those expressions and the definition of ω_1 imply that, for each speculator m and the Central Bank,

$$\begin{aligned} E\left[p_1|\delta_v(m)\right] &= A_0 + A_1x(m) + A_1B_0(M-1) \\ &\quad + A_1B_1(M-1)\rho\delta_v(m) + A_1C_0 + A_1C_1\psi\delta_v(m), \end{aligned} \tag{A-9}$$
$$E\left[p_1|\delta_{CB},\delta_T\right] = A_0 + A_1x_{CB} + MA_1B_0 + MA_1B_1\rho\delta_{CB}, \tag{A-10}$$

respectively. Eq. (A-9) leads to the following expression for the first order condition of the maximization of each speculator m's $E\left[\pi\left(m\right)|\delta_{v}\left(m\right)\right]$:

$$\begin{aligned}&p_{0}+\delta_{v}\left(m\right)-A_{0}-2A_{1}x\left(m\right)-\left(M-1\right)A_{1}B_{0}\\&-\left(M-1\right)A_{1}B_{1}\rho\delta_{v}\left(m\right)-A_{1}C_{0}-A_{1}C_{1}\psi\delta_{v}\left(m\right)=0.\end{aligned} \tag{A-11}$$

The second order condition is satisfied as $-2A_{1}<0$. For Eq. (A-11) to be true, it must be that

$$p_{0}-A_{0} = \left(M+1\right)A_{1}B_{0}+A_{1}C_{0}, \tag{A-12}$$

$$2A_{1}B_{1} = 1-\left(M-1\right)A_{1}B_{1}\rho-A_{1}C_{1}\psi. \tag{A-13}$$

The distributional assumptions of Sections 2.1 and 2.2 imply that

$$\begin{aligned}&\arg\min_{x_{CB}}E\left[L|\delta_{CB},\delta_{T}\right]=\arg\min_{x_{CB}}\left[\gamma A_{1}^{2}x_{CB}^{2}+2\gamma A_{1}^{2}MB_{0}x_{CB}\right.\\&+2\gamma A_{1}^{2}MB_{0}\rho\delta_{CB}x_{CB}+2\gamma A_{0}A_{1}x_{CB}-2\gamma p_{T}A_{1}x_{CB}+\left(1-\gamma\right)A_{0}x_{CB}\\&+\left(1-\gamma\right)A_{1}x_{CB}^{2}+\left(1-\gamma\right)MA_{1}B_{0}x_{CB}+\left(1-\gamma\right)MA_{1}B_{1}\rho\delta_{CB}x_{CB}\\&\left.-\left(1-\gamma\right)p_{0}x_{CB}-\left(1-\gamma\right)\delta_{CB}x_{CB}\right].\end{aligned} \tag{A-14}$$

The first order condition of this minimization is then given by

$$\begin{aligned}&2\gamma A_{1}^{2}x_{CB}+2\gamma A_{1}^{2}MB_{0}+2\gamma A_{1}^{2}MB_{0}\rho\delta_{CB}+2\gamma A_{0}A_{1}-2\gamma p_{T}A_{1}\\&+\left(1-\gamma\right)A_{0}+2\left(1-\gamma\right)A_{1}x_{CB}+\left(1-\gamma\right)MA_{1}B_{0}\\&+\left(1-\gamma\right)MA_{1}B_{1}\rho\delta_{CB}-\left(1-\gamma\right)p_{0}-\left(1-\gamma\right)\delta_{CB}=0.\end{aligned} \tag{A-15}$$

The second order condition is also satisfied as $2\gamma A_{1}^{2}+2\left(1-\gamma\right)A_{1}>0$. Eq. (A-15) and $d\equiv\frac{\gamma}{1-\gamma}$ imply that

$$p_{0}-A_{0} = 2A_{1}C_{0}+MA_{1}B_{0}+2dA_{1}^{2}C_{0}+2dA_{1}^{2}MB_{0}+2dA_{0}A_{1}-2d\overline{p}_{T}A_{1}, \tag{A-16}$$

$$2A_{1}C_{1} = 1-MA_{1}B_{1}\rho-2dA_{1}^{2}C_{1}-2dA_{1}^{2}MB_{1}\rho, \tag{A-17}$$

$$A_{1}C_{2} = dA_{1}-dA_{1}^{2}C_{2}, \tag{A-18}$$

for our conjectures to be true. It ensues from Eq. (A-18) that $C_{2}=\frac{d}{1+dA_{1}}$. We further observe that those conjectures also imply that the order flow ω_{1} must be normally distributed with mean $E\left(\omega_{1}\right)=MB_{0}+C_{0}$ and variance

$$var\left(\omega_{1}\right)=MB_{1}^{2}\rho\sigma_{v}^{2}\left[1+\left(M-1\right)\rho\right]+C_{1}^{2}\psi\sigma_{v}^{2}+2MB_{1}C_{1}\psi\rho\sigma_{v}^{2}+\sigma_{z}^{2}+C_{2}^{2}\sigma_{T}^{2}. \tag{A-19}$$

Since $cov\left(v,\omega_{1}\right)=MB_{1}\rho\sigma_{v}^{2}+C_{1}\psi\sigma_{v}^{2}$ and $p_{1}=E\left(v|\omega_{1}\right)$ in equilibrium (Condition 2), it follows that

$$p_{1}=p_{0}+\frac{\left(MB_{1}\rho\sigma_{v}^{2}+C_{1}\psi\sigma_{v}^{2}\right)\left(\omega_{1}-MB_{0}-C_{0}\right)}{MB_{1}^{2}\rho\sigma_{v}^{2}\left[1+\left(M-1\right)\rho\right]+C_{1}^{2}\psi\sigma_{v}^{2}+2MB_{1}C_{1}\psi\rho\sigma_{v}^{2}+\sigma_{z}^{2}+C_{2}^{2}\sigma_{T}^{2}}. \tag{A-20}$$

Thus, our conjecture for p_1 yields

$$A_0 = p_0 - MA_1B_0 - A_1C_0, \tag{A-21}$$

$$A_1 = \frac{MB_1\rho\sigma_v^2 + C_1\psi\sigma_v^2}{MB_1^2\rho\sigma_v^2\left[1+(M-1)\rho\right] + C_1^2\psi\sigma_v^2 + 2MB_1C_1\psi\rho\sigma_v^2 + \sigma_z^2 + C_2^2\sigma_T^2}. \tag{A-22}$$

The expressions for A_0, A_1, B_0, B_1, C_0, and C_1 in Proposition 2 must solve the system made of Eqs. (A-12), (A-13), (A-16), (A-17), (A-21), and (A-22) to represent a linear equilibrium. For both Eqs. (A-12) and (A-21) to be true, it must be that $B_0 = 0$. Defining $A_1C_0 = p_0 - A_0$ from Eq. (A-12) and plugging it into Eq. (A-16) leads us to $A_0 = p_0 + 2dA_1\left(p_0 - \overline{p}_T\right)$ and $C_0 = 2d\left(\overline{p}_T - p_0\right)$. We are left with the task of finding A_1, B_1, and C_1. Solving Eq. (A-13) for B_1 and Eq. (A-17) for C_1 we get

$$B_1 = \frac{1 - A_1C_1\psi}{A_1\left[2+(M-1)\rho\right]}, \tag{A-23}$$

$$C_1 = \frac{1 - MA_1B_1\rho\left(1+2dA_1\right)}{2A_1\left(1+dA_1\right)}, \tag{A-24}$$

respectively. The system made of Eqs. (A-23) and (A-24) implies that $B_1 = \frac{2(1+dA_1)-\psi}{A_1 f(A_1)}$ and $C_1 = \frac{[2+(M-1)\rho]-M\rho(1+2dA_1)}{A_1 f(A_1)}$, where $f\left(A_1\right) = 2\left[2+(M-1)\rho\right]\left(1+dA_1\right) - M\psi\rho\left(1+2dA_1\right)$. Next, we replace the above expressions for B_1 and C_1 in Eq. (A-22) to get the following sextic polynomial in A_1,

$$g_6A_1^6 + g_5A_1^5 + g_4A_1^4 + g_3A_1^3 + g_2A_1^2 + g_1A_1 + g_0 = 0, \tag{A-25}$$

where it is a straightforward but tedious exercise to show that, for the parameter restrictions in Sections 2.1 and 2.2,

$$g_0 = -\sigma_v^2\left[M\rho\left(2-\psi\right)^2 + \psi\left(2-\rho\right)^2\right] < 0, \tag{A-26}$$

$$g_1 = -2\sigma_v^2 d\left\{M\rho\left[8 - 6\psi - \psi^2\left(1-\rho\right)\right] + 2\psi\left(2-\rho\right)^2\right\} < 0, \tag{A-27}$$

$$\begin{aligned} g_2 &= \sigma_z^2 M\rho\left[M\rho\left(2-\psi\right)^2 + 4\left(2-\rho\right)\left(2-\psi\right)\right] + \sigma_T^2 d^2\left[M\rho\left(2-\psi\right) + 2\left(2-\rho\right)\right]^2 \\ &+\sigma_v^2 d^2\left\{M\rho\left[4M\rho\psi\left(1-\psi\right) + \psi^2\left(7-4\rho\right) + 5\psi\left(4-\rho\right) - 24\right] + 5\psi\rho\left(4-\rho\right) - 20\psi\right\}, \end{aligned} \tag{A-28}$$

$$\begin{aligned} g_3 &= 2\sigma_z^2 dM\rho\left\{M\rho\left[8 - \psi\left(10-3\psi\right)\right] + 2\left[16 - 5\psi\left(2-\rho\right) + 8\rho\right]\right\} \\ &+2\sigma_v^2 d^3\left\{4M^2\rho^2\psi\left(1-\psi\right) + 2M\rho\left[\psi^2\left(1-\rho\right) + \psi\left(5-2\rho\right) - 4\right] - \psi\left(2-\rho\right)^2\right\} \\ &+4\sigma_T^2 d^3\left\{M^2\rho^2\left[2 - \psi\left(3-\psi\right)\right] + M\rho\left[8 - 3\psi\left(2-\rho\right) - 4\rho\right] + 2\left(2-\rho\right)^2\right\}, \end{aligned} \tag{A-29}$$

$$g_4 = 4\sigma_T^2 d^4 \left[M\rho\left(1-\psi\right)+\left(2-\rho\right)\right]^2 + 4\sigma_v^2 d^4 M\rho\left[M\rho\psi\left(1-\psi\right)+\psi\left(2-\rho\right)-1\right]$$
$$+\sigma_z^2 d^2 \left\{M^2\rho^2\left[24+\psi\left(13\psi-36\right)\right]+12M\rho\left[8-3\psi\left(2-\rho\right)-4\rho\right]+24\left(2-\rho\right)^2\right\} > 0, \quad \text{(A-30)}$$

$$g_5 = 4\sigma_z^2 d^3 \left\{M^2\rho^2\left[4-\psi\left(7-3\psi\right)\right]+M\rho\left[16-7\psi\left(2-\rho\right)-8\rho\right]+4\left(2-\rho\right)^2\right\} > 0, \quad \text{(A-31)}$$

$$g_6 = 4\sigma_z^2 d^4 \left[M\rho\left(1-\psi\right)+\left(2-\rho\right)\right]^2 > 0, \quad \text{(A-32)}$$

and that either $sign\left(g_3\right) = sign\left(g_2\right) = sign\left(g_1\right)$, $sign\left(g_4\right) = sign\left(g_3\right) = sign\left(g_2\right)$, or $sign\left(g_4\right) = sign\left(g_3\right)$ and $sign\left(g_2\right) = sign\left(g_1\right)$, i.e., that only one change of sign is possible while proceeding from the lowest to the highest power. Descartes' Rule then implies that the polynomial of Eq. (A-25) has only one positive real root satisfying the second order conditions for both the speculators' and the Central Bank's optimization problems. This root, λ_{CB}, is therefore the unique linear Bayesian Nash equilibrium of the amended economy of Section 2.2. ■

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Table 1. BrokerTec: Descriptive statistics

This table reports the mean (μ), standard deviation (σ), and first-order autocorrelation coefficient ($\rho(1)$) for variables of interest in the BrokerTec database of quotes for *on-the-run* two-year, three-year, five-year, and ten-year U.S. Treasury notes, and thirty-year U.S. Treasury bonds (i). Summary statistics are computed over *i)* the full sample period (January 2, 2001 to December 31, 2007, in Panel A); *ii)* the earlier subsample (January 2, 2001 to December 31, 2004, in Panel B); and *iii)* the later subsample (January 3, 2005 to December 31, 2007, in Panel C). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. Treasury note and bond prices are quoted in points, i.e., are reported as fraction of par multiplied by 100. $S_{i,t}$ is the average daily quoted bid-ask price spread in basis points (*bps*), i.e., further multiplied by 100. $\Delta S^B_{i,t} \equiv S_{i,t} - S^B_{i,t}$, where $S^B_{i,t}$ is the average bid-ask price spread over the most recent previous 22 trading days when no POMO occurred. $V_{i,t}$ is the daily trading volume, in billions of U.S. dollars. A " * ", " ** ", or " *** " indicates statistical significance at the 10%, 5%, or 1% level, respectively.

Table 1. (*Continued*)

		$S_{i,t}$			$\Delta S_{i,t}^B$			$V_{i,t}$		
Segment	N	μ	σ	$\rho(1)$	μ	σ	$\rho(1)$	μ	σ	$\rho(1)$
Panel A: BrokerTec, 01/2001-12/2007										
Two-year	1,680	1.096	0.46	0.97***	-0.030***	0.28	0.43***	$20.890	$15.21	0.93***
Three-year	964	1.334	0.77	0.97***	-0.028***	0.30	0.33***	$7.829	$4.95	0.95***
Five-year	1,684	1.535	0.97	0.95***	-0.064***	0.58	0.48***	$17.595	$12.99	0.95***
Ten-year	1,561	2.975	1.70	0.96***	-0.083***	0.91	0.39***	$15.243	$12.44	0.94***
Thirty-year	1,514	8.322	6.97	0.96***	-0.237***	3.06	0.46***	$1.878	$1.82	0.93***
Panel B: BrokerTec, 01/2001-12/2004										
Two-year	972	1.299	0.52	0.96***	-0.052***	0.37	0.43***	$11.790	$5.80	0.94***
Three-year	407	1.947	0.88	0.97***	-0.058**	0.47	0.33***	$3.960	$1.97	0.94***
Five-year	976	2.009	1.04	0.94***	-0.112***	0.76	0.48***	$9.025	$5.36	0.95***
Ten-year	854	4.036	1.67	0.95***	-0.153***	1.22	0.39***	$5.951	$4.47	0.94***
Thirty-year	803	13.086	6.56	0.96***	-0.442***	4.18	0.46***	$0.525	$0.47	0.92***
Panel C: BrokerTec, 01/2005-12/2007										
Two-year	708	0.816	0.03	0.99***	0.001**	0.01	0.35***	$33.383	$15.27	0.92***
Three-year	557	0.886	0.04	0.99***	-0.006***	0.04	0.46***	$10.656	$4.55	0.95***
Five-year	708	0.881	0.05	0.99***	0.001	0.03	0.58***	$29.409	$10.99	0.94***
Ten-year	707	1.693	0.07	0.99***	0.002	0.05	0.53***	$26.466	$9.34	0.94***
Thirty-year	711	2.942	0.41	0.99***	-0.005	0.30	0.54***	$3.405	$1.55	0.93***

Table 2. POMOs: Descriptive statistics

This table reports summary statistics for all permanent open market operations (POMOs) conducted by the Federal Reserve Bank of New York (FRBNY) in the secondary U.S. Treasury market over *i)* the full sample period (January 2, 2001 to December 31, 2007, in Panel A); *ii)* the earlier subsample (January 2, 2001 to December 31, 2004, in Panel B); and *iii)* the later subsample (January 3, 2005 to December 31, 2007, in Panel C). All POMOs executed over this sample period were purchases of Treasury securities ($POMO_{i,t} > 0$). POMOs are sorted by the segment (i) of the yield curve targeted by the FRBNY — *on-the-run* two-year, three-year, five-year, and ten-year U.S. Treasury notes, and thirty-year on-the-run U.S. Treasury bonds. Specifically, we label a FRBNY transaction as *i)* a two-year POMO if the remaining maturity of the traded security is between zero and four years; *ii)* a three-year POMO if the remaining maturity of the traded security is between one and five years; *iii)* a five-year POMO if the remaining maturity of the traded security is between three and seven years; *iv)* a ten-year POMO if the remaining maturity of the traded security is between eight and twelve years; and *v)* a thirty-year POMO if the remaining maturity of the traded security is greater than twelve years. N is the number of days when POMOs occurred over the sample period. N_d is the average number of intraday POMOs executed by the FRBNY. μ is the mean total daily principal traded, in billions of U.S. dollars; σ is the corresponding standard deviation.

	$POMO_{i,t}$											
	Panel A: 01/2001-12/2007				Panel B: 01/2001-12/2004				Panel C: 01/2005-12/2007			
Segment	N	N_d	μ	σ	N	N_d	μ	σ	N	N_d	μ	σ
Total	217	27.9	$1.108	$0.44	153	28.8	$1.073	$0.48	64	25.5	$1.194	$0.29
Two-year	162	27.4	$1.152	$0.51	117	28.8	$1.136	$0.55	45	23.1	$1.194	$0.40
Three-year	120	23.8	$0.852	$0.39	80	22.9	$0.734	$0.34	40	25.3	$1.088	$0.38
Five-year	78	24.3	$0.565	$0.40	50	23.6	$0.430	$0.30	28	25.2	$0.805	$0.45
Ten-year	36	15.6	$0.343	$0.25	24	14.4	$0.306	$0.21	12	17.6	$0.416	$0.32
Thirty-year	32	20.9	$0.390	$0.24	23	20.4	$0.375	$0.17	9	22.4	$0.428	$0.38

Table 3. POMOs and Market Liquidity

This table reports means of daily bid-ask price spread changes $\Delta S_{i,t}^B \equiv S_{i,t} - S_{i,t}^B$ (labeled $\overline{\Delta S_{i,t}^B}$, in bps) for on-the-run Treasury notes and bonds (i) over days when POMOs occurred in the *same* maturity bracket ($I_{i,t}^{CB} = 1$), and over days when *any* POMO occurred ($I_t^{CB} = 1$). $S_{i,t}$ is the average bid-ask price spread on day t; $S_{i,t}^B$ is the average bid-ask price spread over the most recent previous 22 trading days when no POMO occurred. We also report OLS estimates of the following regression model (Eq. (8)):

$$\Delta S_{i,t}^B = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,CB} I_{i,t}^{CB} + \varepsilon_{i,t},$$

where $Calendar_t$ is a vector of day-of-the-week, monthly, and year fixed effects, $\Delta D_{i,t}^B \equiv D_{i,t} - D_{i,t}^B$, $\Delta C_{i,t}^B \equiv C_{i,t} - C_{i,t}^B$, $D_{i,t}$ and $C_{i,t}$ are the daily modified duration and convexity, and $D_{i,t}^B$ and $C_{i,t}^B$ are their averages over the most recent previous 22 trading days when no POMO occurred, respectively, for both same-maturity ($I_{i,t}^{CB} = 1$) and any-maturity POMOs ($I_t^{CB} = 1$). Means and regression coefficients are estimated over the full BrokerTec sample period (January 2, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. R_a^2 is the adjusted R^2. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,CB}$.

	Same-maturity POMOs					Any-maturity POMOs				
Segment	$\overline{\Delta S_{i,t}^B}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	N	$\alpha_{i,CB}$	R_a^2	N
Two-year	-0.135***	157	-0.086***	9%	1,682	-0.130***	211	-0.089***	9%	1,682
Three-year	-0.056**	58	0.010	11%	964	-0.087***	102	-0.023	11%	964
Five-year	-0.240***	75	-0.140*	11%	1,686	-0.248***	210	-0.149***	12%	1,686
Ten-year	-0.129	33	0.029	9%	1,563	-0.366***	196	-0.257***	10%	1,563
Thirty-year	-0.643	28	-0.378	8%	1,516	-0.778***	200	-0.539**	7%	1,516

Table 4. POMOs and Market Liquidity: Robustness

This table reports means of daily bid-ask price spread changes $\Delta S_{i,t}^B \equiv S_{i,t} - S_{i,t}^B$ (labeled $\overline{\Delta S_{i,t}^B}$, in bps) for on-the-run Treasury notes and bonds (i) over days when POMOs occurred in the *same* ($I_{i,t}^{CB} = 1$) or *any* maturity bracket ($I_t^{CB} = 1$). We also report OLS estimates of the following regression model (Eq. (8)):

$$\Delta S_{i,t}^B = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,CB} I_{i,t}^{CB} + \varepsilon_{i,t},$$

as described in Table 3. Means and regression coefficients are estimated over *i)* the earlier BrokerTec subsample (January 2, 2001 to December 31, 2004, in Panel A); *ii)* the later BrokerTec subsample (January 3, 2005 to December 31, 2007, in Panel B); and *iii)* the full GovPX sample period (January 2, 2001 to December 31, 2004, in Panel C). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. R_a^2 is the adjusted R^2. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,CB}$.

	Same-maturity POMOs					Any-maturity POMOs				
Segment	$\overline{\Delta S_{i,t}^B}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	N	$\alpha_{i,CB}$	R_a^2	N
Panel A: BrokerTec, 01/2001-12/2004										
Two-year	-0.186***	114	-0.115***	13%	973	-0.184***	149	-0.126***	14%	973
Three-year	-0.116**	24	0.030	21%	407	-0.183***	45	-0.027	21%	407
Five-year	-0.365***	49	-0.211**	17%	977	-0.350***	148	-0.212***	17%	977
Ten-year	-0.193	21	-0.043	15%	855	-0.533***	134	-0.377***	16%	855
Thirty-year	-0.892	19	-0.430	11%	804	-1.096***	138	-0.671*	9%	804
Panel B: BrokerTec, 01/2005-12/2007										
Two-year	0.000	43	0.000	14%	709	0.000	62	0.000	14%	709
Three-year	-0.014***	34	-0.007	26%	557	-0.011***	57	-0.004	26%	557
Five-year	-0.003	26	-0.002	26%	709	-0.003*	62	-0.003	26%	709
Ten-year	-0.016**	12	-0.004	17%	708	-0.004	62	-0.002	17%	708
Thirty-year	-0.118*	9	-0.082*	19%	712	-0.069***	62	-0.032	19%	712
Panel C: GovPX, 01/2001-12/2004										
Two-year	-0.210***	117	-0.174***	8%	972	-0.197***	153	-0.177***	8%	972
Three-year	-0.210	23	-0.219	17%	345	-0.417	44	-0.473	18%	345
Five-year	-0.038	49	0.055	4%	932	-0.284***	152	-0.244**	4%	932
Ten-year	-0.342	21	0.020	2%	718	-0.473***	148	-0.348	3%	718
Thirty-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 5. POMOs and Information Heterogeneity

This table reports OLS slope coefficients $a^x_{i,CB}$ of the regression of average daily bid-ask spread and price changes $\Delta S^B_{i,t}$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (i) over *same*-maturity or *any*-maturity POMO days ($I^{CB}_{i,t} = 1$ or $I^{CB}_t = 1$) on the contemporaneous realizations of $SSDF_q$ — the simple scaled average of the standardized dispersion of analyst forecasts of six macroeconomic variables from SPF, see Section 4.2.1 — multiplied by the difference between $SSDF_q^{70^{th}}$ (the top 70$^{\text{th}}$ percentile of its empirical distribution) and $SSDF_q^{30^{th}}$ (the bottom 30$^{\text{th}}$ percentile of its empirical distribution). We label these differences as $\overline{\Delta\Delta S^{B,x}_{i,t}} = a^x_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$for $X_t = SSDF_q$. We also estimate, again by OLS, the interaction of either $I^{CB}_{i,t}$ or I^{CB}_t with $X_t = SSDF_q$ in the following regression model (Eq. (9)):

$$\Delta S^B_{i,t} = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D}\Delta D^B_{i,t} + \alpha_{i,\Delta C}\Delta C^B_{i,t} + \alpha_{i,CB} I^{CB}_{i,t} + \alpha^x_{i,CB} I^{CB}_{i,t} X_t + \varepsilon_{i,t},$$

where $X_t = SSDF_q$. We report these cross-product coefficients as $\Delta\alpha^x_{i,CB} = \alpha^x_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$, again in bps. Means and regression coefficients are estimated over the full sample period (January 2, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. R^2_a is the adjusted R^2. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha^x_{i,CB}$.

	Same-maturity POMOs					Any-maturity POMOs				
Segment	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^x_{i,CB}$	R^2_a	N	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^x_{i,CB}$	R^2_a	N
Two-year	-0.104***	157	-0.076***	10%	1,682	-0.107***	211	-0.082***	11%	1,682
Three-year	0.011	58	0.010	11%	964	-0.023	102	-0.020	11%	964
Five-year	-0.240***	75	-0.162	12%	1,686	-0.206***	210	-0.158***	12%	1,686
Ten-year	-0.328*	33	-0.320*	9%	1,563	-0.361***	196	-0.311***	11%	1,563
Thirty-year	-1.550**	28	-1.589**	9%	1,516	-0.247	200	-0.201	7%	1,516

Table 6. POMOs and Fundamental Uncertainty

This table reports OLS slope coefficients $a^{x}_{i,CB}$ of the regression of average daily bid-ask spread and price changes $\Delta S^{B}_{i,t}$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (i) over *same*-maturity or *any*-maturity POMO days ($I^{CB}_{i,t} = 1$ or $I^{CB}_{t} = 1$) on the contemporaneous realizations of $EURVOL_m$ — the monthly average of daily Eurodollar implied volatility from Bloomberg, see Section 4.2.2 — multiplied by the difference between $EURVOL^{70^{th}}_m$ (the top 70[th] percentile of its empirical distribution) and $EURVOL^{30^{th}}_m$ (the bottom 30[th] percentile of its empirical distribution). We label these differences as $\overline{\Delta\Delta S^{B,x}_{i,t}} = a^{B,x}_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$ for $X_t = EURVOL_m$. We also estimate, again by OLS, the interaction of either $I^{CB}_{i,t}$ or I^{CB}_{t} with $X_t = EURVOL_m$ in the following regression model (Eq. (9)):

$$\Delta S^{B}_{i,t} = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D}\Delta D^{B}_{i,t} + \alpha_{i,\Delta C}\Delta C^{B}_{i,t} + \alpha_{i,CB} I^{CB}_{i,t} + \alpha^{x}_{i,CB} I^{CB}_{i,t} X_t + \varepsilon_{i,t},$$

where $X_t = EURVOL_m$. We report these cross-product coefficients as $\Delta\alpha^{x}_{i,CB} = \alpha^{x}_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$ and $\Delta\beta^{x}_{i,CB} = \beta^{x}_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$, again in bps. Means and regression coefficients are estimated over the full sample period (January 2, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. R^2_a is the adjusted R^2. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha^{x}_{i,CB}$.

	Same-maturity POMOs					Any-maturity POMOs				
Segment	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^{x}_{i,CB}$	R^2_a	N	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^{x}_{i,CB}$	R^2_a	N
Two-year	-0.015	157	-0.007	9%	1,682	-0.026	211	-0.017	9%	1,682
Three-year	-0.067*	58	0.033	11%	964	-0.130***	102	-0.087***	12%	964
Five-year	-0.040	75	-0.030	11%	1,686	-0.023	210	-0.015	11%	1,686
Ten-year	-0.393	33	-0.318**	9%	1,563	-0.123	196	-0.094	10%	1,563
Thirty-year	-1.009	28	-0.389	8%	1,516	-0.452	200	-0.143	7%	1,516

Table 7. POMOs and POMO Policy Uncertainty

This table reports OLS slope coefficients $a^x_{i,CB}$ of the regression of average daily bid-ask spread and price changes $\Delta S^B_{i,t}$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (i) over *same*-maturity or *any*-maturity POMO days ($I^{CB}_{i,t} = 1$ or $I^{CB}_t = 1$) on the contemporaneous realizations of $FEDVOL_m$ — the monthly average of daily volatility of the federal funds rate, from the FRBNY, see Section 4.2.3 — multiplied by the difference between $FEDVOL^{70^{th}}_m$ (the top 70$^{\text{th}}$ percentile of its empirical distribution) and $FEDVOL^{30^{th}}_m$ (the bottom 30$^{\text{th}}$ percentile of its empirical distribution). We label these differences as $\overline{\Delta\Delta S^{B,x}_{i,t}} = a^x_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$ for $X_t = FEDVOL_m$. We also estimate, again by OLS, the interaction of either $I^{CB}_{i,t}$ or I^{CB}_t with $X_t = FEDVOL_m$ in the following regression model (Eq. (9)):

$$\Delta S^B_{i,t} = \alpha_{i,0} + \alpha_{i,C}Calendar_t + \alpha_{i,\Delta D}\Delta D^B_{i,t} + \alpha_{i,\Delta C}\Delta C^B_{i,t} + \alpha_{i,CB}I^{CB}_{i,t} + \alpha^x_{i,CB}I^{CB}_{i,t}X_t + \varepsilon_{i,t},$$

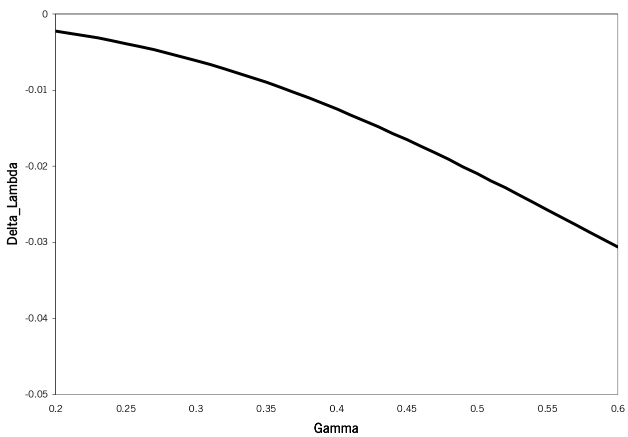
where $X_t = FEDVOL_m$. We report these cross-product coefficients as $\Delta\alpha^x_{i,CB} = \alpha^x_{i,CB}\left(X^{70^{th}}_t - X^{30^{th}}_t\right)$, again in bps. Means and regression coefficients are estimated over the full sample period (January 2, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and December 7, 2007. N is the number of observations. R^2_a is the adjusted R^2. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha^x_{i,CB}$.

	Same-maturity POMOs					Any-maturity POMOs				
Segment	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^x_{i,CB}$	R^2_a	N	$\overline{\Delta\Delta S^{B,x}_{i,t}}$	N	$\Delta\alpha^x_{i,CB}$	R^2_a	N
Two-year	-0.061***	157	-0.046*	10%	1,682	-0.076***	211	-0.058**	10%	1,682
Three-year	0.059**	58	0.036*	11%	964	0.082***	102	0.062***	12%	964
Five-year	-0.236**	75	-0.178	12%	1,686	-0.094**	210	-0.052	12%	1,686
Ten-year	0.109	33	0.037	9%	1,563	-0.105**	196	-0.116**	10%	1,563
Thirty-year	-1.673*	28	-1.815***	9%	1,516	0.012	200	-0.163	7%	1,516

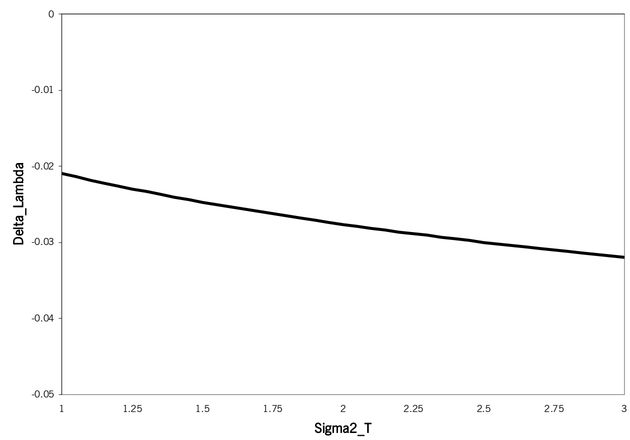
Figure 1. Market Liquidity and Central Bank Intervention

This figure plots the difference between equilibrium price impact in the presence and in the absence of the stylized Central Bank of Eq. (4), $\Delta\lambda \equiv \lambda_{CB} - \lambda = \lambda_{CB} - \frac{\sigma_v\sqrt{M\rho}}{\sigma_z[2+(M-1)\rho]}$, as a function of either γ (the Central Bank's commitment to achieve its policy, in Figure 1a), σ_T^2 (the uncertainty surrounding that policy, in Figure 1b), ρ (the degree of correlation of the speculators' private signals, in Figure 1c), or σ_v^2 (the fundamental uncertainty, in Figure 1d), when $\sigma_v^2 = \sigma_z^2 = \sigma_T^2 = 1$, $\rho = 0.5$, $\psi = 0.5$, $\gamma = 0.5$, and $M = 500$.

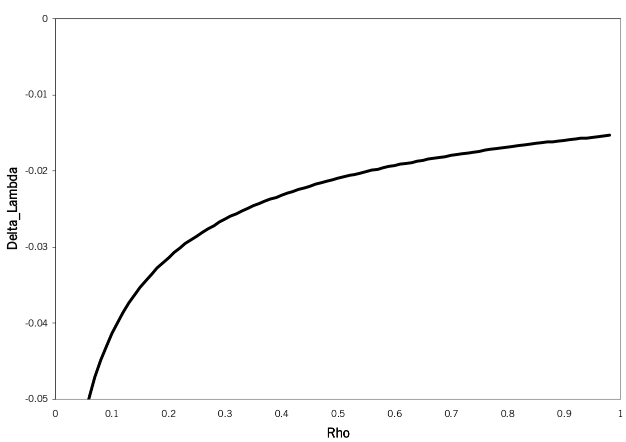
a) $\Delta\lambda$ versus γ



b) $\Delta\lambda$ versus σ_T^2



c) $\Delta\lambda$ versus ρ



d) $\Delta\lambda$ versus σ_v^2

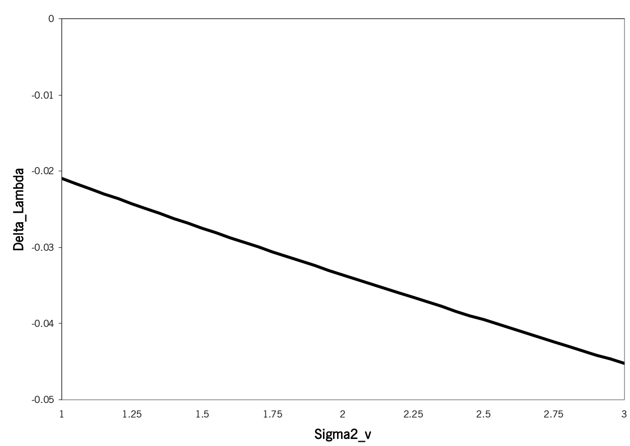
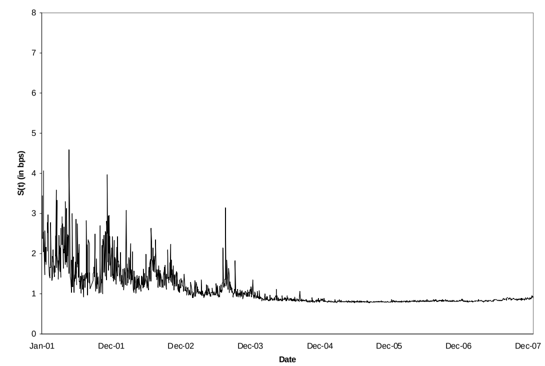


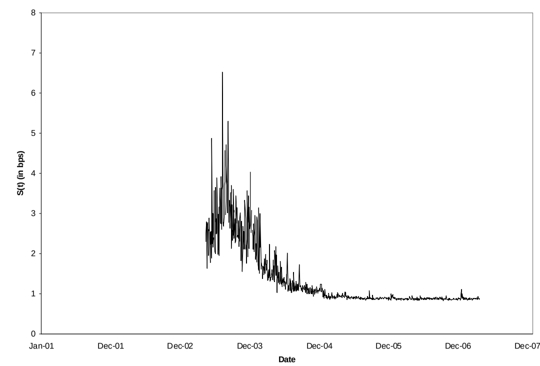
Figure 2. U.S. Treasury Notes and Bonds: Bid-Ask Spreads

This figure plots daily bid-ask price spreads $S_{i,t}$ for *on-the-run* two-year, three-year, five-year, and ten-year U.S. Treasury notes, and thirty-year U.S. Treasury bonds (i) on the BrokerTec platform between January 2, 2001 and December 31, 2007. Data for three-year notes is available only between May 7, 2003 and December 7, 2007. Treasury note and bond prices are quoted in points, i.e., are reported as fraction of par multiplied by 100. $S_{i,t}$ is the average daily quoted bid-ask price spread in basis points (bps), i.e., further multiplied by 100.

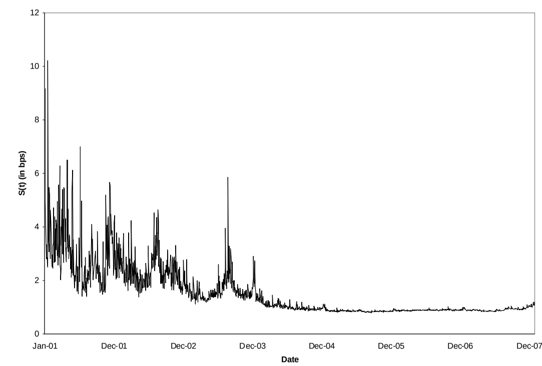
a) Two-year U.S. Treasury notes



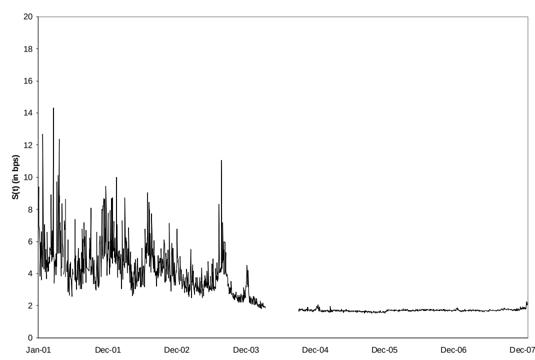
b) Three-year U.S. Treasury notes



c) Five-year U.S. Treasury notes



d) Ten-year U.S. Treasury notes



e) Thirty-year U.S. Treasury bonds

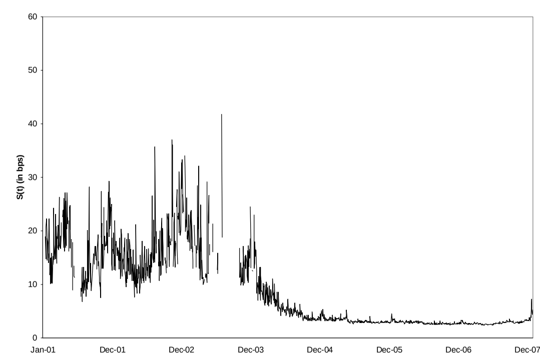


Figure 3. POMOs and Fed Funds rates

This figure plots the daily total principal amounts of U.S. Treasury securities purchased ($POMO_t > 0$) or sold ($POMO_t < 0$) by the FRBNY as POMOs (left axis, in billions of dollars), as well as both the federal funds effective daily rate from overnight trading in the federal funds market (dotted line, right axis, in percentage terms, i.e., multiplied by 100) and its corresponding target set by the FOMC (solid line, right axis), between January 2, 2001 and December 31, 2007.

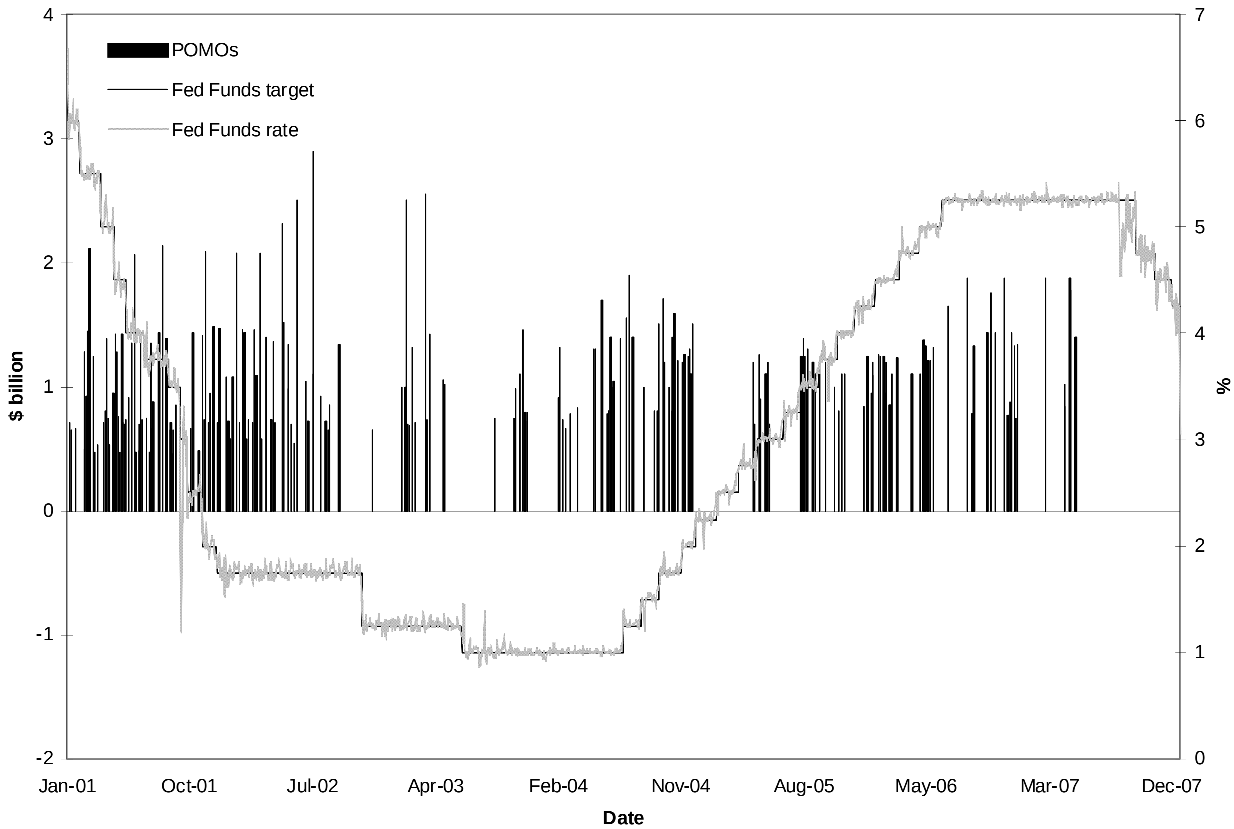
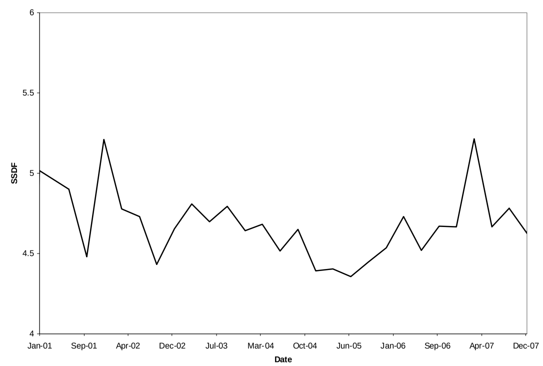


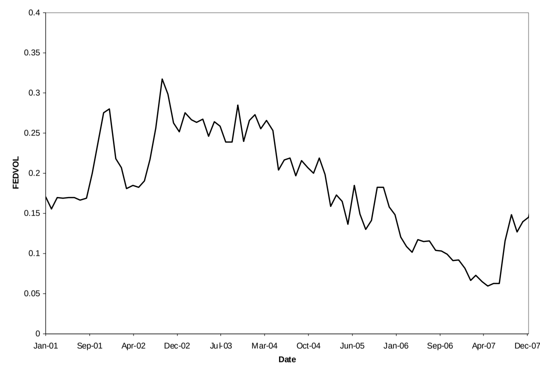
Figure 4. Marketwide Information Aggregates

Figure 4a plots $SSDF_q$, the scaled simple average of standardized standard deviation of professional forecasts of six U.S. macroeconomic announcements (Unemployment, Non Farm Payroll, Nominal GDP, CPI, Industrial Production, and Housing Starts), from SPF (see Section 4.2.1). Figure 4b plots $EURVOL_m$, the monthly average of daily Eurodollar implied volatility (in percentage), from Bloomberg (see Section 4.2.2). Figure 4c plots $FEDVOL_m$, the monthly average of daily volatility of the federal funds rate (in percentage), form the FRBNY (see Section 4.2.3).

a) $SSDF_q$



b) $EURVOL_m$



c) $FEDVOL_m$