

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 monetary policy stance previously set and publicly announced by the Federal Open Market Committee (FOMC). Using a stylized, parsimonious model of speculative trading, we show that *i)* this form of government intervention *improves* market liquidity, and *ii)* the extent of this improvement depends on the market's information environment. Evidence from a novel sample of FRBNY's POMOs during the 2000s 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 *non-public target* level consistent with the monetary policy stance (and accompanying federal funds target rate) previously set and publicly announced by the Federal Open Market Committee (FOMC).

The frequency and magnitude of POMO trades are nontrivial: Even prior to the recent crisis, between January 2001 and December 2007, the Federal Reserve Bank of New York (FRBNY) executed POMOs nearly once every eight working days, for an average daily principal amount of \$1.11 billion. Importantly, while the FOMC’s decisions are public and informative about its current and planned stance of monetary policy, the Federal Reserve’s *non-public* targeted level of reserves has been *uninformative* about that stance since the mid-1990s (see Akhtar, 1997; Edwards, 1997; Harvey and Huang, 2002; Sokolov, 2009; among others).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 stylized 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 role of informed trading in Treasury securities for their process of price

¹See also the FRBNY’s website at <http://www.newyorkfed.org/markets/pomo/display/index.cfm>.

formation. In the model's basic setting, strategic trading in a risky asset by 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 by making their trading activity more cautious and MMs more vulnerable to adverse selection.

The introduction of a stylized Central Bank consistent in spirit 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 (Krishnamurthy, 2002; Vayanos and Vila, 2009; Greenwood and Vayanos, 2010; Krishnamurthy and Vissing-Jorgensen, 2010). 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.²

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 Bank is intervening. Accordingly, we also show that greater uncertainty among market participants about the Central Bank's policy target magnifies the improvement in market liquidity accompanying its trades. Greater such uncertainty both makes it more difficult for the MMs to

²See also the surveys in Lyons (2001) and Neely (2005). Other studies (e.g., Evans and Lyons, 2005; Chari, 2007; Pasquariello, 2010) postulate that government intervention in currency markets may worsen their liquidity because of inventory management considerations.

learn about the uninformative policy target from the order flow and alleviates their perceived adverse selection from trading with informed speculators.

We assess the empirical relevance of our model using a comprehensive, recently available sample of intraday price data for 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) — and a proprietary dataset of all POMOes conducted by the FRBNY during the 2000s. POMOes 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 over the pre-crisis period 2001-2007 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 POMOes in the corresponding maturity bracket and on days when any POMO occurred. The latter may be due to the relatively high degree of substitutability among Treasury securities documented in prior studies (e.g., Cohen, 1999; Greenwood and Vayanos, 2010; D’Amico and King, 2013). Estimated liquidity improvements are both economically and statistically significant. For instance, on days when any POMO occurred, quoted bid-ask spreads decline by an average of 7% (for three-year bonds) to 16% (for five-year notes) of their sample means, and 25% (for thirty-year bonds) to 46% (for two-year notes) of the sample standard deviation of their daily changes. Only a fraction of these effects displays within the ninety-minute morning interval during which the FRBNY always executes its trades, suggesting that the impact of POMOes on MMs’ adverse selection risk is not short-lived.

This evidence is unlikely to stem from POMOes’ 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 (and often stronger when) controlling for various calendar effects and bond-specific characteristics, as well as for various Treasury market conditions; *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 and holds during that sub-period as well, i.e., despite the crisis’ implications for liquidity 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 information environment of 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 or Treasury bond option 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. Inoue (1999) also 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. Harvey and Huang (2002) conjecture that such increase may be attributed to the effect of OMOs on market participants' expectations. 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.

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.³ 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 informed trading 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 a normal distribution with mean p_0 and variance σ_s^2 and that, for any two speculators m and j , $cov[S_v(m), S_v(j)] = cov[v, S_v(m)] = \sigma_v^2$. As in Pasquariello and Vega (2009), we also parametrize the dispersion of speculators' private information by imposing that $\sigma_s^2 = \frac{1}{\rho}\sigma_v^2$ and $\rho \in (0, 1)$, such that each speculator's information advantage (or endowment) 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 $E[\delta_v(j)|\delta_v(m)] = \rho\delta_v(m)$. Thus, the parameter ρ represents the correlation between any two information endowments $\delta_v(m)$ and $\delta_v(j)$: The lower (higher) is ρ , the less (more)

³For more details on the microstructure of the U.S. Treasury market, see Fabozzi and Fleming (2004) and Mizrach and Neely (2009).

correlated — i.e., the more (less) *heterogeneous* — is speculators' private information.⁴

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 of 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*: $p_1(\omega_1) = E(v | \omega_1)$.⁵

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

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

Some of the properties of the equilibrium of Proposition 1 are standard in the literature since Kyle (1985). Imperfectly competitive speculators are aware of the potential impact of their trades on prices; thus, despite being risk-neutral, they trade on their private information cautiously

⁴The analysis that follows yields similar implications if based on more general information structures for speculators' heterogeneous private signals (albeit at the cost of greater analytical complexity) — e.g., $S_v(m) = v + \varepsilon(m)$ such that $\text{cov}[S_v(m), S_v(j)] \neq \text{cov}[v, S_v(m)]$ (see Caballé and Krishnan, 1994; Foster and Viswanathan, 1996; Pasquariello, 2007a; Pasquariello and Vega, 2007; Albuquerque and Vega, 2009) — or if endowing speculators with the same private signal about the asset payoff v — e.g., $S_v(m) = v$ (Kyle, 1985) or $S_v(m) = v + \varepsilon$ (Subrahmanyam, 1991).

⁵Equivalently, competition is assumed to force MMs' expected profits to zero.

($|x(m)| < \infty$) to dissipate less of it. Accordingly, speculators' optimal trading strategies depend both on their information endowments about the traded asset's payoff v ($\delta_v(m)$) and market liquidity (λ): $x(m) = \frac{1}{\lambda[2+(M-1)\rho]} \delta_v(m)$ in Eq. (2). 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, and different from Kyle (1985), $x(m)$ and λ also depend on ρ , the correlation among speculators' information endowments. Intuitively, as in Pasquariello and Vega (2007), when speculators' private information is more heterogeneous (ρ closer to zero), each speculator perceives to have greater monopoly power on her signal, because more of it is perceived to be known to her alone. Hence, each speculator trades on her signal 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 it. 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.⁶ 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 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

⁶To 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), Edwards (1997), Harvey and Huang (2002), Board of Governors (2005), and Afonso et al. (2010) provide detailed discussions of U.S. monetary policy and its implementation. Further information is also available on the FRBNY website at <http://www.newyorkfed.org/markets/openmarket.html>.

Federal Reserve — on a daily basis.⁷ 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. POMOs are *outright* (or *permanent*) trades of government bonds affecting the supply of nonborrowed reserves *permanently*. TOMOs are repurchasing agreements by which the Desk 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 (overnight or term basis) affecting the supply of nonborrowed reserves only *temporarily*.

For many years, the FOMC did not publicly announce changes in its stance of monetary policy, forcing market participants to infer them from the Desk’s OMOs and the observed level of the federal funds rate. Media reports would then publicize the resulting market consensus. As such, the Desk conducted outright operations (POMOs) only infrequently (e.g., a few times a year) and only when pursuing sizable permanent changes in the supply for reserves. According to Edwards (1997, p. 862), this “could, and on a few occasions did, lead to misunderstandings about the stance of policy or to delays in recognizing changes.” However, on February 4, 1994, after the FOMC voted to tighten monetary policy for the first time in five years, Chairman Alan Greenspan decided to disclose that new stance immediately and unequivocally to the public in a press release “to avoid any misunderstanding of the Committee’s purposes.”⁸ Since then, the FOMC has made its monetary policy decisions increasingly transparent — e.g., by pre-announcing its intentions and disclosing the federal funds target rate to all market participants — therefore making the Desk’s OMOs *virtually uninformative* about the Federal Reserve’s future monetary policy stance over our sample period (Akhtar, 1997; Edwards, 1997; Harvey and Huang, 2002; Sokolov, 2009).

Importantly, while uninformative about the FOMC’s monetary policy stance, the actions by the Desk at the FRBNY are neither meaningless nor “mechanical” (Akhtar, 1997, p. 34). Given that stance, the timing, direction, and magnitude of FRBNY trades along the Treasury maturity structure are driven by nonborrowed *reserve paths* (or *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., Edwards, 1997; Harvey and Huang, 2002; Board of Governors, 2005).⁹ Every day, the FRBNY sets a nonborrowed reserve target

⁷See Furfine (1999) for a detailed analysis of the microstructure of the federal funds market.

⁸See <http://www.federalreserve.gov/fomc/19940204default.htm>.

⁹See <http://www.newyorkfed.org/aboutthefed/fedpoint/fed32.html> for a discussion of the FRBNY’s review of financial conditions in advance of its OMOs.

consistent with the FOMC’s monetary policy stance and the federal funds target rate (e.g., see Edwards, 1997). If the FRBNY expects *persistent* imbalances between the demand and supply of nonborrowed reserves (e.g., due to trends in the demand for U.S. currency in circulation) leading to a persistent violation of its reserve target, it may affect the supply through POMOs.¹⁰ If those imbalances are instead expected to be *temporary*, the FRBNY may enter TOMOs; accordingly, TOMOs occur much more frequently (nearly every trading day) than POMOs. These observations imply 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.

In this study we intend to analyze the process of price formation in the secondary Treasury market in the presence of outright trades (i.e., POMOs) by the FRBNY’s Desk in that market. To that purpose, we amend the basic one-shot model of outright trading of Section 2.1 to allow for the presence of a stylized Central Bank alongside speculators and liquidity traders. As noted earlier, the Desk also routinely executes short-lived round-trip trades (i.e., TOMOs) in the Treasury repo market. As such, our setting is inadequate at capturing TOMOs’ transitory nature, heterogeneous holding-period intervals (i.e., overnight or term basis), and significantly higher recurrence. In addition, as we discuss below, uncertainty about government intervention plays an important role in our model. According to Edwards (1997), the temporary reserve imbalances leading the federal funds rate to temporarily move away from the FOMC’s target are “more technical,” i.e., more mechanical in nature. Thus, there may be considerably less uncertainty among market participants about the Desk’s short-term reserve objectives behind its TOMOs. Nevertheless, in our subsequent empirical analysis we explicitly control for any spillover effect of TOMOs on Treasury market liquidity (see Section 4.2.4).

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 \bar{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:

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

where $\gamma \in (0, 1)$ is known to all market participants.

¹⁰For instance, according to Akhtar (1997, p. 18), “currency demand is the largest single factor requiring [nonborrowed] reserve injections [i.e., POMO purchases], because it has a strong growth trend which reflects, primarily, the growth trend of the economy.”

The specification of Eq. (4) is similar in spirit to Stein (1989), Bhattacharya and Weller (1997), Vitale (1999), and Pasquariello (2010).¹¹ The first component, $(p_1 - p_T)^2$, 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 p_T 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 and Vayanos, 2010; Krishnamurthy and Vissing-Jorgensen, 2010). Intuitively, in the presence of elastic demand curves for Treasury securities, changes in their supply induced by the Desk’s outright trades affect their prices. Hence, 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.

The second component, $(p_1 - v)x_{CB}$, captures the cost of the intervention as any deviation from purely speculative trading motives (e.g., as in Bhattacharya and Weller, 1997, Eq. (1)). 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. Accordingly, the Federal Reserve has often voiced concern about the effects of capital losses from its OMOs on its balance sheet and remittances to the U.S. Treasury.¹² The greater is γ the more important is the first component relative to the second in the Central Bank’s loss function, i.e., the more important it deems the pursuit of p_T relative to its cost. In other words, the coefficient γ can be interpreted as the relative preference weight placed by the Central Bank on its policy motives. 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 .

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 $\sigma_{CB}^2 = \frac{1}{\psi}\sigma_v^2$, where the precision parameter $\psi \in (0, 1)$ and $cov[S_v(m), S_{CB}] = cov(v, S_{CB}) = \sigma_v^2$ (as for $S_v(m)$ in Section 2.1). However, as noted earlier, since the mid-1990s the FOMC no longer employs POMOs to communicate changes in its stance of monetary policy to market participants. Hence,

¹¹When 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.

¹²E.g., see the published minutes of the FOMC meetings in December 2012, January 2013, and March 2013 (at <http://www.federalreserve.gov/monetarypolicy/files/>).

POMOs no longer convey *payoff-relevant* information about traded Treasury securities. We make this observation operational in our stylized model of bond trading by further imposing that the Central Bank's policy target p_T is *uninformative* about the traded asset's liquidation value v , i.e., that $\text{cov}(v, p_T) = \text{cov}[S_v(m), p_T] = \text{cov}(S_{CB}, p_T) = 0$. Both uncertainty about and uninformative nature of p_T are meant to capture the unanticipated nature of FRBNY trades in government bonds following public, informational FOMC decisions. In our setting, we can think of these policy decisions as translating into the commonly known distribution of the risky asset's liquidation value 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 implementation of the announced informative FOMC policy in the marketplace (e.g., about the Desk's uninformative 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 $\delta_T \equiv p_T - \bar{p}_T$, 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*

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

by each speculator m 's demand strategy

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

and by the Central Bank's demand strategy

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

where the ratio $d \equiv \frac{\gamma}{1-\gamma}$ is the Central Bank's relative degree of commitment to its policy target, and 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 (via $E[\delta_v(j) | \delta_v(m)]$), as in the equilibrium of Proposition 1)

but also for the trading activity of the Central Bank (via $E[\delta_{CB}|\delta_v(m)]$) 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 uses its information advantage δ_{CB} to account for speculators’ trading activity (via $E[\delta_v(m)|\delta_{CB}]$) when devising its optimal trading strategy x_{CB} . As such, x_{CB} of Eq. (7) also depends on the number of speculators (M) and the heterogeneity of their private information (ρ). According to Proposition 2, x_{CB} 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, $(\bar{p}_T - p_0)$, 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.

One cannot solve for the unique equilibrium price impact λ_{CB} of Proposition 2 in closed form. Therefore, we characterize its properties by means of numerical examples rather than formal comparative statics. Our model is sufficiently stylized for tractability not to be amenable to calibration from observed market data. However, these examples are based on “reasonable” parameter values given our goals, i.e., not only ensuring that an equilibrium for the economy can be found (see the Appendix) but also consistent with the above discussion on the nature of the FRBNY’s POMO policy. In particular, we assume that 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). 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). The ensuing inference is robust to alternative parametrizations of the economy.

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.¹³ 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 flow.

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.¹⁴ 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 these implications of our numerical examples.

Remark 1 *Under reasonable model parametrizations, the presence of a Central Bank improves market liquidity ($\Delta\lambda < 0$) by an extent ($|\Delta\lambda|$) increasing in γ , σ_T^2 , and σ_v^2 , and decreasing in ρ .*

2.3 Model Extensions

The above discussion makes clear that our model's main predictions about the effects of government intervention on market liquidity stem from the conditional uncertainty among market participants (i.e., given their information endowments) about the Central Bank's *non-public, uninformative* policy target p_T . With knowledge of the Central Bank's loss function (Eq. (4)),

¹³I.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.

¹⁴E.g., unreported analysis shows that $|\Delta B_1\rho|$ is increasing in ρ .

rational MMs would account for the portion of its trading activity driven by a *public*, uninformative p_T in the aggregate order flow ω_1 , thus making such pursuit ineffective (Vitale, 1999). Credible, *fully* informative announcements about asset fundamentals (v), like those by the FOMC since 1994, would be fully and immediately incorporated into market participants' expectations and equilibrium prices ($p_1 = v$), thus thwarting speculation and making the market infinitely deep for liquidity trading ($\lambda_{CB} = 0$).¹⁵

Our model's implications for market liquidity are also qualitatively unaffected (yet its analysis is more analytically involved) by making the Central Bank's non-public policy target p_T at least *partially* correlated with the traded asset's payoff v (as in Bhattacharya and Weller, 1997). For instance, assume that p_T is some unspecified function of the Central Bank's private, informative signal S_{CB} such that $cov[p_T, S_{CB}] = \sigma_{CB}^2$ and $cov[S_v(m), p_T] = cov(v, p_T) = \sigma_v^2$. It can be shown that in those circumstances the presence of a Central Bank continues to improve market liquidity, albeit less so than when its policy target is uninformative — even *ceteris paribus* for unconditional policy uncertainty σ_T^2 .

Intuitively, $cov(v, p_T) > 0$ has three additional effects on MMs' perceived adverse selection risk, relative to when $cov(v, p_T) = 0$. First, MMs can learn about p_T from fundamental information in the aggregate order flow ω_1 , i.e., are confronted with less uninformative uncertainty in ω_1 ; this may increase the MMs' perceived adverse selection risk relative to when $cov(v, p_T) = 0$. Second, a partially informative policy target p_T is less costly for the Central Bank to pursue given its loss function of Eq. (4), hence making government intervention more aggressive and ω_1 more informative about v ; this may decrease MMs' perceived adverse selection risk. Third, the Central Bank's pursuit of a partially informative policy target makes speculators' private information about v less valuable and their trading activity more cautious; this may increase the MMs' perceived adverse selection risk. Once again, this amended model cannot be solved in closed form. However, under reasonable parametrizations of our economy, the first and third effects of $cov(v, p_T) > 0$ prevail upon the second, yielding a mitigated improvement in market liquidity relative to when $cov(v, p_T) = 0$ but one displaying the same properties as in Remark 1.

Lastly, we noted earlier that our stylized Central Bank's loss function of Eq. (4) is based on extant theoretical literature on government intervention (e.g., see Bhattacharya and Weller, Eq. (1)). Eq. (4) is both tractable and consistent with this literature's intuitive notion that governments may balance expected trading losses against expected policy success when setting their intervention strategies. However, the above discussion also implies that our model's main

¹⁵For 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).

predictions are likely to be robust to any alternative loss function yielding nontrivial optimal intervention (i.e., $|x_{CB}| < \infty$) driven (at least partly) by the pursuit of (at least partly uninformative) policy targets.

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 during the 2000s.

3.1 Bond Market Data

Our basic sample is made of 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 1, 2001 and December 31, 2007, i.e., immediately prior to the recent financial crisis. We analyze the more turbulent crisis period 2008-2009 in Section 4.2.2. 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 voice-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 is 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.¹⁶ 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).¹⁷ To eliminate interdealer

¹⁶BrokerTec 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.

¹⁷Although trading takes place nearly continuously during the week, 95% of trading volume occurs during those

brokers' posting errors, we filter all quotes within this interval following the procedure described in Fleming (2003).¹⁸ Lastly, we augment the BrokerTec database with information on important fundamental characteristics (daily modified duration, $D_{i,t}$, and convexity, $C_{i,t}$) of all notes and bonds in our sample (from Morgan Markets, J.P. Morgan's data portal).

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 role of informed speculation for Treasury market liquidity. To better capture such a role, we focus our analysis on *daily* measures of market liquidity for each security in our sample. The econometrician does not observe the precise timing and extent of informed speculation throughout the day; hence, narrowing the estimation window may lead to underestimate its full effects on market liquidity around POMOs (e.g., since those effects may manifest nonuniformly over several hours after POMOs occurred; Neely (2005) and Pasquariello (2007b) further discuss these issues when surveying the vast empirical literature on Central Bank interventions in currency markets). 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). We nonetheless also analyze *intraday* measures of liquidity in Section 4.2.3.

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 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 from measurement error in the dependent variable (e.g., Greene, 1997).

hours (e.g., Fleming, 1997). Outside that interval, fluctuations in bond prices are likely due to illiquidity.

¹⁸We 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) because of the accompanying significant illiquidity in the Treasury market (e.g., Hu et al., 2010).

Accordingly, in this paper we measure the liquidity of each on-the-run Treasury security i with $S_{i,t}$, the daily (i.e., from open to close) average of its quoted intraday *price* bid-ask spreads $S_i = A_i - B_i$. Treasury notes and bonds trade in units of par notional (i.e., of face value), which is set at \$1,000. Consistent with market conventions (e.g., Fleming, 2003), Treasury notes and bond prices A_i and B_i in our sample are in points, i.e., are expressed as a *percentage* of par (where one point is one percent of par) multiplied by 100. Thus, bid-ask spreads S_i are in basis points (*bps*, where one basis point is one percent of one point) further multiplied by 100. Bid-ask spreads are virtually without measurement error. There is an extensive literature relating their magnitude and dynamics to informed trading (see O’Hara, 1995, for a review). In addition, price spreads are comparable over time and across all Treasury securities in our sample since each security’s spread is computed relative to the same face value. Accordingly, we show in Section 4.2.3 that proportional spreads yield nearly identical inference. 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 direct estimates of price impact and well-known episodes of poor liquidity in that market.¹⁹ 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 securities in our sample. 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 further discuss this feature of the data and address its implications for our analysis in Section 4.2.1. Since being discontinued in 1998, three-year notes have been issued by the U.S. Treasury only between February 2003 and May 2007, and from November 2007 onward.²⁰ Data for three-year notes also has significant gaps in BrokerTec market coverage, restricting our analysis of that maturity

¹⁹See 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

²⁰E.g., see http://www.treasurydirect.gov/indiv/research/history/histtime/histtime_notes.htm.

segment to the sub-period 05/2003-03/2007. Figure 2 reveals occasional gaps in coverage for ten-year notes and thirty-year bonds as well. Bid-ask spreads for Treasury securities are increasing (and their liquidity is generally decreasing) with their maturity. 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 (i.e., $\$200,000,000 \times 1.096/10,000 = \$21,920$), an amount routinely available on BrokerTec 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

Our basic sample is a database of all permanent (outright) open market operations (POMOs) executed by the Federal Reserve Bank of New York (FRBNY) between January 1, 2001 and December 31, 2007.²¹ As noted earlier, we consider POMO activity during the crisis period 2008-2009 in Section 4.2.2. 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 (“Fed Time;” see Akhtar, 1997; Harvey and Huang, 2002; D’Amico and King, 2013), i.e., when intraday market liquidity is relatively high (Fleming, 1997; Mizrach and Fleming, 2009). This process is made of multiple steps. Between 10:00 a.m. and 10:30 a.m. (“Release Time”), 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 10:45 a.m. and 11:30 a.m. (“Closing Time”). 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

²¹This database is available at http://www.newyorkfed.org/markets/OMO_transaction_data.html.

of nonborrowed reserves in the monetary system.²²

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. Characterizing these maturity brackets is unavoidably subjective. As in D’Amico and King (2013), 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. The first three brackets are partially overlapping because of the high substitutability of shorter-maturity Treasury securities (e.g., D’Amico and King, 2013). As we show next, our inference is unaffected by this sorting procedure. The extremely 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 also robust to alternative and/or non-overlapping 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 basic 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 25 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

²²Importantly, 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.”

notes. While sizeable, these amounts are significantly lower than sample average daily trading volume not only in the on-the-run Treasury securities in our dataset (between \$1.9 billion and \$20.9 billion; see $V_{i,t}$ in Table 1) but also in the whole secondary U.S. Treasury market (\$469 billion).²³ Figure 3 plots the daily total par amount of the FRBNY’s POMO’s ($POMO_t$, 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. POMO’s 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. Importantly, the Desk executed exclusively purchases ($POMO_t, POMO_{i,t} > 0$) between 2001 and 2007, *regardless of the interest rate environment*, both in aggregate (Figure 3) and in each of the maturity brackets (Table 2). This behavior reflects the Desk’s efforts to accommodate the persistent growth in the demand for U.S. money (mirroring the growth in the economy) by expanding the supply of nonborrowed reserves (Akhtar, 1997; Edwards, 1997) and is consistent with our prior observation that POMO’s are uninformative about the FOMC’s monetary policy stance over our sample period.

4 Empirical Analysis

In this section we test the implications of our model for the impact of POMO’s on the process of price formation in the secondary market for U.S. Treasury securities. We proceed in two steps. First, we test whether POMO’s improve Treasury market liquidity. Second, we assess whether this effect can be attributed to that market’s information environment, as uniquely postulated by our model.

4.1 POMO’s and Market Liquidity

The main prediction of our stylized model is that outright trades by the FRBNY (POMO’s) lower the equilibrium price impact of order flow ($\Delta\lambda \equiv \lambda_{CB} - \lambda < 0$, Remark 1). Intuitively, this outcome stems from uninformative POMO’s 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 POMO’s occur.

²³This 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>. Government interventions in currency markets are of similar relative magnitude (e.g., see Neely, 2005; Pasquariello, 2007b).

To test this prediction, we use an event study methodology based on a well-established literature analyzing the impact of exogenous public announcements on asset prices (e.g., see Andersen et al., 2003, 2007; and references therein). These studies estimate that impact using only announcement days to mitigate omitted variable biases. We begin by defining liquidity changes on any POMO day as $\Delta S_{i,t}^B \equiv S_{i,t} - S_{i,t}^B$, the difference between the average bid-ask price spread on the day a POMO occurred, $S_{i,t}$, and a benchmark pre-intervention level, $S_{i,t}^B$. 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., $S_{i,t}^B = S_{i,t-1}$). Instead, we compute $S_{i,t}^B$ as the average bid-ask price spread over the most recent previous 22 trading days when no POMO occurred (e.g., Pasquariello, 2007b). In Section 4.2.3 we show that alternative pre-intervention intervals lead to similar inference. We then compute means 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 $I_t^{CB} = 1$), because of extant evidence of relatively high substitutability of on-the-run Treasury securities (e.g., Cohen, 1999; Greenwood and Vayanos, 2010; D’Amico and King, 2013).²⁴ We report these averages, labeled $\overline{\Delta S_{i,t}^B}$, in Table 3.²⁵

Consistent with our model, these *univariate* tests show that mean daily bid-ask spreads *decline* on both *same-maturity* and *any-maturity* POMO days. Estimates for $\overline{\Delta S_{i,t}^B}$ in Table 3 are always negative, much larger than their sample 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 about \$380,000 ($\overline{\Delta S_{i,t}^B} = (-0.215/10,000) \times \17.6 billion) — i.e., by 37% of the sample 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

²⁴Spillover 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).

²⁵The 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 on-the-run three-year notes (whose issuance only resumed in 2003 after a five-year hiatus; see Section 3.1.1).

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, as noted earlier, bid-ask spreads on the BrokerTec platform have considerably tightened — and trading volume has likewise increased — over our sample period, especially 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 a *multiple regression* event-study model of bid-ask price spread changes, i.e., for only same-maturity ($I_{i,t}^{CB} = 1$) or any-maturity POMO days ($I_t^{CB} = 1$), as follows:

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T}Trend_t + \gamma_{i,\Delta D}\Delta D_{i,t}^B + \gamma_{i,\Delta C}\Delta C_{i,t}^B + \varepsilon_{i,t}, \quad (8)$$

where $Trend_t$ is a time-trend variable, $\Delta D_{i,t}^B \equiv D_{i,t} - D_{i,t}^B$, $\Delta C_{i,t}^B \equiv C_{i,t} - C_{i,t}^B$, 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. We consider additional explicit controls in Section 4.2.4. Estimates of the intercept $\gamma_{i,CB}$ in Eq. (8) measure average changes in Treasury bid-ask spreads on POMO days (i.e., relative to the prior 22 non-POMO days) net of calendar effects and contemporaneous changes in bond characteristics. We also specify a similar model using *all* trading days:

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

where either $I_t = I_{i,t}^{CB}$ or $I_t = I_t^{CB}$, and $Calendar_t$ is a vector of day-of-the-week, month, and year dummies.²⁶ Estimates of the event dummy coefficient $\alpha_{i,CB}$ in Eq. (9) capture any additional effect of POMOs on $\Delta S_{i,t}^B$ relative to its average over *all other* trading days in the sample period (i.e., the constant $\alpha_{i,0}$).

We estimate these regressions Eqs. (8) and (9) for each on-the-run maturity in our database separately by Ordinary Least Squares (OLS). We evaluate the statistical significance of the

²⁶The 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 Eqs. (8) and (9).

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., $\gamma_{i,CB} < 0$ and $\alpha_{i,CB} < 0$) both when same-maturity and any-maturity POMO occur. Controlling for calendar effects and bond characteristics strengthens our inference: For instance, all estimated intercepts $\gamma_{i,CB}$ in Eq. (8) are larger (in absolute magnitude) than the corresponding means $\overline{\Delta S_{i,t}^B}$. As in prior event-study research, POMO's liquidity externalities are instead smaller when estimated over all trading days (i.e., $|\alpha_{i,CB}| < |\gamma_{i,CB}|$). Regardless of the methodology used, the estimated decline in bid-ask spread accompanying POMO days remains both statistically and economically significant — e.g., amounting on average to 53% [14%] of the corresponding sample mean (in Table 1), and to more than 50% [25%] of the standard deviation of the corresponding spread change (also in Table 1), when measured by $\gamma_{i,CB}$ [$\alpha_{i,CB}$].

4.2 POMO's and Market Liquidity: Robustness

The evidence in Table 3 suggests that Treasury market liquidity improves on POMO days, consistent with the main prediction of our model. In this section, we assess the robustness of this evidence and its conformity to alternative interpretations.

4.2.1 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 gradual migration of most trading in on-the-run Treasury securities from the voice-brokered GovPX platform to two electronic platforms — BrokerTec and eSpeed. In addition, Table 2 and Figure 3 also indicate that POMO's occur nearly twice more often over 2001-2004 than over 2005-2007.

As noted earlier, our regression specifications include time-trend and calendar variables to control for deterministic changes in bid-ask spreads over the sample period 2001-2007. We further assess the effect of the changing characteristics of our sample in two ways. First, we estimate $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,CB}$, and $\alpha_{i,CB}$ separately within either the earlier subsample 2001-2004 (in Panel A of Table 4) or the later one 2005-2007 (in Panel B of Table 4). According to our model (Remark 1), government intervention improves market liquidity by a greater extent when liquidity is already

low (and adverse selection risk high), e.g., because of high fundamental uncertainty (as in 2001-2004). Consistently, Table 4 indicates that while bid-ask spreads for Treasury securities tend to be lower on POMO days in both subperiods, estimates for $\overline{\Delta S_{i,t}^B} < 0$, $\gamma_{i,CB} < 0$, and $\alpha_{i,CB} < 0$ are larger and more often significant in the earlier (low-liquidity, high-POMO frequency) subperiod than in the later (high-liquidity, low-POMO frequency) one. Thus, this evidence may provide further support for our model. We explore more directly the role of fundamental uncertainty for our inference in Section 4.3.2.

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 $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,CB}$, 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 use of BrokerTec data.

4.2.2 The 2008 Financial Crisis

We also extend our analysis to the recent period of financial turmoil in the aftermath of the collapse of Bear Stearns and Lehman Brothers in 2008. Our model is not designed to capture both the determinants of Treasury market liquidity and the unique nature of government intervention in those special circumstances. With this caveat in mind, times of distress may be accompanied by high fundamental uncertainty (high σ_v^2) and rapidly deteriorating market depth (low λ). In those circumstances, government intervention may be aimed at improving marketwide liquidity provision (e.g., by targeting not only price levels [p_T] but also market depth itself [λ]). It is also plausible that in those circumstances, the Central Bank may set potentially informative policy objectives (i.e., $cov(v, p_T) > 0$), reduce uncertainty about them (e.g., lower σ_T^2), and/or pursue them more aggressively (e.g., higher γ in Eq. (4)). As noted in Section 2.3, all of these forces may have large yet conflicting effects on equilibrium market liquidity in the presence of government intervention.

In light of this discussion, we consider the net impact of these forces on our inference by augmenting our sample to include any POMO executed by the FRBNY over the immediate crisis period between January 1, 2008 and December 31, 2009. Importantly, this period encompasses the Federal Reserve’s pursuit of significant “quantitative easing” via POMOs. At the March 2009 FOMC meeting, and contrary to its established modus operandi, the Federal Reserve announced its intention to execute extraordinary large POMOs (and some details about their characteristics) in advance, when directing the Desk to purchase up to \$300 billion of long-term Treasury

securities over the subsequent six months (e.g., see Figure 3). The Desk executed this policy program — known as Large-Scale Asset Purchases (LSAP) — over several trading days between March 25 and October 29, 2009. In those cases, the Desk first announced the broad maturity segment it targeted and the days in which it was planning to trade about two weeks in advance (D’Amico and King, 2013). Subsequent LSAP programs over 2010-2012 (known as LSAP-2 and LSAP-3) followed similar procedures (Kitsul, 2013). Summary statistics on these POMO days are in Panel D of Table 2. There are 75 POMO days over the immediate crisis period 2008-2009. Interestingly, in a few of them (18, all in 2008) the Desk sold Treasury securities. Average daily par amounts accepted at POMO auctions during 2008-2009 are several times larger than during the basic sample period 2001-2007. According to Panel D of Table 1 and Figure 2, bid-ask spreads on Treasury securities also widen considerably during 2008-2009, e.g., by an average of 27% relative to their pre-crisis means over 2005-2007 (in Panel C of Table 1).²⁷

Table 4 reports estimates for $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,CB}$, and $\alpha_{i,CB}$ over the extended sample 2001-2009 (Panel D), as well as over the sub-period 2008-2009 for POMO purchases (Panel E) and POMO sales (Panel F). According to Table 4, *i*) our inference is qualitatively unaffected by the inclusion of the immediate crisis period; and *ii*) *both* POMO purchases and sales during the crisis period are accompanied on average by tighter bid-ask spreads — as predicted by our model — although the estimated improvement in liquidity is statistically significant almost exclusively for POMO purchases (perhaps due to the small number of POMO sales in the merged BrokerTec/POMO sample). Consistently, Kitsul (2013) finds that (various measures of) Treasury market liquidity improved in correspondence with all LSAPs (and LSAP-related announcements) by the Desk between March 2009 and October 2012. We conclude that the estimated liquidity externalities of POMOs during the recent financial crisis are consistent with our model’s main prediction, notwithstanding the crisis’ likely effects on both liquidity provision and government intervention policy in the Treasury market. We consider alternative interpretations of these findings in Section 4.2.4 below.

4.2.3 Alternative Specifications

The empirical evidence in Table 3 is based on comparing daily averages of intraday bid-ask price spreads for on-the-run Treasury securities on days when POMOs occurred ($S_{i,t}$) to those averages on the past 22 days when no POMOs occurred ($S_{i,t}^B$). Over our sample period, in only two cases does this approach require as many as 37 prior trading days to find 22 prior non-POMO

²⁷Afonso 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.

trading days; in most other cases, $S_{i,t}^B$ is computed over no longer than six trading weeks prior to a POMO day. Our inference is qualitatively unaffected by employing either longer or shorter trailing intervals for $S_{i,t}^B$. For instance, univariate and multivariate estimates of spread changes on POMO days relative to five-day (one-day) pre-intervention levels — $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,CB}$, and $\alpha_{i,CB}$ in Panel G of Table 4 (untabulated) — are qualitatively similar to (or even stronger than) those reported in Table 3.

As noted earlier, daily averaging of intraday bid-ask spreads allows us to mitigate any bias from non-informational microstructure noise in the data (typically salient at the intraday frequency), as well as to account for the unobservable, possibly nonuniform within-day intensity of informed speculation. Both issues may weaken the statistical and economic significance of estimated liquidity externalities of government intervention. With this in mind, we consider here the impact of POMOs on intraday Treasury market liquidity.

Comparing estimates of Treasury market liquidity over portions of POMO days before versus either during or after the ninety-minute Fed Time interval when the FRBNY typically announces and executes its POMOs (10:00 a.m. to 11:30 a.m.; see Section 3.2) may not be appealing for several reasons. According to Fleming (1997), Treasury bid-ask price spreads are wider in the morning (e.g., until 9:00 a.m.) and afternoon hours (e.g., after 1:30 p.m.) but significantly tighter around Fed Time (e.g., until past 12 p.m.). This significant intraday seasonality makes the estimation of liquidity changes around POMO auctions at Fed Time challenging. In addition, the model of Section 2 predicts that government intervention improves equilibrium market liquidity ($\Delta\lambda \equiv \lambda_{CB} - \lambda < 0$) under the assumption that all market participants are aware of the presence (λ_{CB}) or absence (λ) of the Central Bank. It is plausible that a subset of market participants (e.g., the primary dealers bidding at Treasury auctions) may have advance knowledge of an impending POMO auction minutes before its terms are publicly announced at Release Time (10 a.m.).²⁸ Thus, comparing average measures of Treasury market liquidity within POMO days to those averages within non-POMO days is closer in spirit to the model’s notion of $\Delta\lambda$. Lastly, as noted earlier, the effects of POMO auctions on perceived adverse selection risk may display over several hours after their occurrence.

In light of this discussion, as in Sokolov (2009), we compute both average bid-ask spreads $S_{i,t}$ and their benchmark pre-intervention levels $S_{i,t}^B$ exclusively over the intraday Fed Time interval, yielding $S_{i,t}^*$ and $S_{i,t}^{B*}$. We then run the same univariate and multivariate tests of Section 4.1 on

²⁸For instance, according to Akthar (1997, p. 48), in the wake of POMOs the Desk has “ongoing contacts with primary dealers [...] about the wide-ranging forces at work in financial markets: changing demands of the dealers’ customers in the securities markets and their interest in particular types of securities; [...] dealers’ expectations about Treasury financing in the period ahead, and potential customer interest in coming financing.”

spread change differentials during Fed Time, $\Delta S_{i,t}^{B*}$. As conjectured above, the ensuing estimates of $\overline{\Delta S_{i,t}^{B*}}$, $\gamma_{i,CB}^*$, and $\alpha_{i,CB}^*$, in Panel H of Table 4, are nearly always negative (consistent with our model’s main prediction) but relatively smaller in magnitude and less often statistically significant than when measured over the entire POMO day (in Table 3).

Studies of the microstructure of equity markets often use percentage bid-ask spreads (Madhavan, 2000; Hasbrouck, 2007). Since stock prices are quoted in price per share and there is significant stock price-level heterogeneity and time-series variation, normalizing stocks’ bid-ask price spreads, e.g., by the midquote, makes them comparable across stocks and over time. We noted earlier that bid-ask price spreads in the secondary market for Treasury notes and bonds (S_i) are quoted as a fraction of their common par value of \$1,000. Thus, their averages $S_{i,t}$ are already comparable across Treasury securities and over time. Our inference is nonetheless qualitatively unaffected by using percentage bid-ask spreads $s_i = (A_i - B_i) / [\frac{1}{2}(A_i + B_i)]$. Panel I of Table 4 reports estimates from the univariate and multivariate tests of Section 4.1 when the dependent variable is changes in the average daily percentage spread, $\Delta s_{i,t}^B \equiv s_{i,t} - s_{i,t}^B$. On-the-run bond price midquotes at all maturities (except at the very long end of the yield curve) tend to be relatively close to par over our sample period. Accordingly, sign and significance of the estimated effect of POMOs on daily percentage bid-ask spreads, $\overline{\Delta s_{i,t}^B}$, $\gamma_{i,CB}^s$, and $\alpha_{i,CB}^s$ are almost identical to those in Table 3.

4.2.4 Alternative Interpretations

The estimated improvement in Treasury market liquidity accompanying POMOs over the sample period 2001-2007 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.²⁹ This may ultimately lead to *wider* bid-ask spreads, contrary to the evidence in Tables 3 and 4.

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 — $POMO_{i,t} > 0$

²⁹For instance, in a sequential model of trading under *symmetric* information, Pasquariello (2010) shows that the mere likelihood (yet not the actual occurrence) of large government intervention may induce competitive dealers to *widen* 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.

($POMO_{i,t} < 0$) — 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, 2013). However, the Desk not only did not sell any Treasury security over the sample period 2001-2007, but also explicitly avoids trading in what the market perceives as “scarce” securities (see Section 3.2).

Alternatively, POMO may affect liquidity provision in the Treasury bond market by altering reserve market conditions for participating dealers with depository facilities, even if those trades had no discernible impact on the market’s information environment (as instead postulated by our model). 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. In addition, and contrary to the predictions of this channel, we noted in Section 4.2.2 that Treasury market liquidity improves in the wake of *both* POMO purchases and sales during the financial crisis period 2008-2009 (see Panels E and F of Table 4).

To further investigate this possibility (as well as further mitigate omitted variable biases), we consider whether our evidence is robust to explicitly controlling for a variety of additional factors affecting market conditions (including liquidity provision) in the secondary market for Treasury securities. These include changes in overnight repo specialness (the difference between overnight general collateral and on-the-run security-specific repo rates; e.g., Krishnamurthy, 2002), recent Treasury auction results (bid-to-cover ratios and number of days since the latest on-the-run auction; Pasquariello and Vega, 2009), number of days since the latest FOMC meeting, each day’s position over the cyclical reserve maintenance period (lasting two weeks, from Thursday [1] to Wednesday [14], during which banks have to keep specified average levels of funds at the Federal Reserve; see Board of Governors, 2005), the amounts traded by the Desk via TOMOs (Sokolov, 2009; Brunetti et al., 2011), and the dates of arguably the most important U.S. macroeconomic announcements (Nonfarm Payroll, Unemployment, Nominal GDP, CPI, Industrial Production, and Housing Starts; e.g., Andersen and Bollerslev, 1998; Pasquariello and Vega, 2007; Brenner et al., 2009). Some of these variables may also be affected by POMO auctions, as well as affect the extent of uncertainty among market participants about the Desk’s POMOs. As noted in Section 2.3 and Remark 1, the positive liquidity externality of government intervention in our model is increasing in market-makers’ and speculators’ perceived uncertainty about the Central

Bank’s policy target (σ_T^2). Thus, any of those market conditions, if attenuating POMO policy uncertainty, may mitigate that externality.³⁰

We then estimate the multiple regressions of Eqs. (8) and (9) for daily and Fed Time average price and percentage spreads, after including those additional controls. Their (untabulated) estimated regression coefficients are most often statistically insignificant. As conjectured, the resulting estimated POMO intercepts ($\gamma_{i,CB}$, $\gamma_{i,CB}^*$, and $\gamma_{i,CB}^s$) and dummy coefficients ($\alpha_{i,CB}$, $\alpha_{i,CB}^*$, and $\alpha_{i,CB}^s$), respectively (in Panels J to L of Table 4), tend to be smaller than those in Table 3 and Panels H and I of Table 4, but remain negative and statistically significant, consistent with the model’s main prediction. Overall, the evidence in Table 4 suggests that the improvement in Treasury market liquidity in the wake of POMOs is unlikely to be systematically explained by their impact on dealers’ inventories, on the relative supply of the traded securities, or on reserve market conditions for liquidity providers.

4.3 POMOs and the Information Environment of the Market

The evidence in Tables 3 and 4 provides strong support for our model’s main prediction (in Remark 1): POMOs executed by the FRBNY’s Desk in the secondary market for Treasury securities meaningfully improve Treasury market liquidity. Our model attributes this effect to the impact of government intervention on the Treasury market’s information environment. In this section, we assess more directly this basic, novel premise of our theory by testing its unique, additional predictions for Treasury market liquidity (also in Remark 1).

4.3.1 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 the heterogeneity of private information about fundamentals among sophisticated Treasury market participants. Marketwide informa-

³⁰In Section 4.3.3 below, we provide additional evidence of this relationship with a more direct proxy for POMO policy uncertainty.

tion heterogeneity is commonly proxied by the standard deviation across professional forecasts of economic and financial variables (e.g., Diether et al., 2002; Green, 2004; Pasquariello and Vega, 2007, 2009; Kallberg and Pasquariello, 2008; Yu, 2011). In this paper we consider two proxies for ρ based on the notion that U.S. macroeconomic variables may contain payoff-relevant information for U.S. Treasury securities; accordingly, numerous studies find that government bond returns and market quality are sensitive to the release of these variables to the public (e.g., see Pasquariello and Vega, 2007; Brenner et al., 2009; and references therein). These proxies employ the only continuously available surveys of U.S. macroeconomic forecasts over our sample period, namely those collected by the Federal Reserve Bank of Philadelphia (the Survey of Professional Forecasters [SFS]) and by Bloomberg.³¹

The SPF, initiated in 1968 by the American Statistical Association and the National Bureau of Economic Research, is commonly used in empirical research on the formation of macroeconomic expectations. Croushore (1993) provides a detailed description of the SPF database. SPF data is available exclusively at the quarterly frequency. For each quarter q , the SPF database contains tens of individual forecasts by private sector economists (working at financial firms, banks, economic consulting firms, university research centers, and Fortune 500 companies) for various macroeconomic variables and at various future horizons. We focus on next-quarter forecasts for the most important of them (as in Section 4.2.4): Nonfarm Payroll, Unemployment, Nominal GDP, CPI, Industrial Production, and Housing Starts. Bloomberg surveys professional forecasts of U.S. macroeconomic announcements at the frequency of their release to the public. This data is available to us only for Nonfarm Payroll, which is released on a monthly basis and is labeled by Andersen and Bollerslev (1998, p. 240) as the “king” of macroeconomic announcements because of its significant impact on financial markets.

We define the dispersion of beliefs among speculators for each macroeconomic variable p in the SPF dataset in quarter q as the standard deviation of all of that variable’s next-quarter forecasts available in that quarter, $SDF_{p,q}$. We similarly compute the monthly standard deviation of all of the Nonfarm Payroll forecasts available in Bloomberg in month m , $SDNF_m$. Since units of measurement differ across macroeconomic variables, we then divide the difference between each $SDF_{p,q}$ (or $SDNF_m$) and its sample mean by its sample standard deviation (e.g., Pasquariello and Vega, 2007) and then add five (to ensure that each information variable is always positive). This yields time series of scaled, standardized dispersion of analyst forecasts, $SSDF_{p,q}$ and $SSDNF_m$. Lastly, we compute our proxies for the *aggregate* degree of information heterogeneity about U.S.

³¹An equally popular monthly survey of professional forecasts of U.S. macroeconomic announcements administered by the International Money Market Services Inc. (MMS) has been discontinued in 2003.

macroeconomic fundamentals as either $SSDF_q$ (the simple average of all available $SSDF_{p,q}$; see Figure 4a) or $SSDNF_m$ (see Figure 4b), such that the greater is either proxy the lower may be ρ in the U.S. Treasury market.

As in Section 4.1, we assess the impact of marketwide information heterogeneity on POMOs' positive liquidity externalities in several ways. We estimate univariate regressions of average bid-ask spread changes $\Delta S_{i,t}^B$ over (same-maturity or any-maturity) POMO days *alone* ($I_t^{CB} = 1$ or $I_t^{CB} = 1$) on the contemporaneous realizations of either $X_t = SSDF_q$ or $X_t = SSDNFP_m$:

$$\Delta S_{i,t}^B = \beta_{i,CB} + \beta_{i,CB}^x X_t + \varepsilon_{i,t}. \quad (10)$$

We also amend the multiple regression models of Eqs. (8) and (9) to include either the information variable X_t ($SSDF_q$ or $SSDNFP_m$) using only POMO days:

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T} Calendar_t + \gamma_{i,\Delta D} \Delta D_{i,t}^B + \gamma_{i,\Delta C} \Delta C_{i,t}^B + \gamma_{i,CB}^x X_t + \varepsilon_{i,t}, \quad (11)$$

or both X_t and its cross-products with same-maturity and any-maturity POMO dummies ($I_t = I_{i,t}^{CB}$ and $I_t = I_t^{CB}$) using all trading days:

$$\begin{aligned} \Delta S_{i,t}^B = & \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,x} X_t \\ & + \alpha_{i,CB} I_t + \alpha_{i,CB}^x I_t X_t + \varepsilon_{i,t}. \end{aligned} \quad (12)$$

Estimates of the slope coefficient $\beta_{i,CB}^x$ in Eq. (10) capture any state dependency (from X_t) in bid-ask spread changes on POMO days *alone*. Estimates of the interaction coefficient $\gamma_{i,CB}^x$ in Eq. (11) capture that state dependency while controlling for calendar effects and changes in bond characteristics. Estimates of the interaction coefficient $\alpha_{i,CB}^x$ in Eq. (12) capture that state-dependency with respect to changes over the *whole* sample period.³²

The linear specifications of Eqs. (10) to (12) are standard in the literature (e.g., see Pasquariello and Vega, 2013) and allow us to estimate the statistical significance of the *continuous* effect of any state variable X_t on POMOs' liquidity externalities. However, the scale of X_t affects the scale of the resulting OLS estimates for $\beta_{i,CB}^x$, $\gamma_{i,CB}^x$, and $\alpha_{i,CB}^x$. Thus, exclusively to ease their interpretation and assess their economic significance, we multiply each of those coefficients by a hypothetical *discrete* increase in the information variable X_t from the bottom (i.e., "low") 30th

³²According to our basic model (see Proposition 1, in Section 2.1) and extant empirical evidence (e.g., Pasquariello and Vega, 2007), the Treasury market's information environment may affect its equilibrium liquidity (λ of Eq. (3)) even in absence of Central Bank interventions (i.e., even in non-POMO days). Thus, our low-frequency information measures X_t are likely to impact both $S_{i,t}$ and $S_{i,t}^B$ such that these effects may cancel out in $\Delta S_{i,t}^B \equiv S_{i,t} - S_{i,t}^B$. Consistently, untabulated estimates of $\alpha_{i,x}$ in Eq. (12) reveal $\Delta S_{i,t}^B$ to be largely insensitive to X_t on non-POMO days.

percentile ($X_t^{30^{th}}$) to the top (i.e., “high”) 70th percentile ($X_t^{70^{th}}$) of its empirical distribution. We report these scaled estimates $\overline{\Delta\Delta S_{i,t}^{B,x}} = \beta_{i,CB}^x \left(X_t^{70^{th}} - X_t^{30^{th}} \right)$, $\Delta\gamma_{i,CB}^x = \gamma_{i,CB}^x \left(X_t^{70^{th}} - X_t^{30^{th}} \right)$, and $\Delta\alpha_{i,CB}^x = \alpha_{i,CB}^x \left(X_t^{70^{th}} - X_t^{30^{th}} \right)$ for either $X_t = SSDF_q$ or $X_t = SSDNFP_m$ in Panels A and B of Table 5, respectively. By construction, $\overline{\Delta\Delta S_{i,t}^{B,x}}$, $\Delta\gamma_{i,CB}^x$, and $\Delta\alpha_{i,CB}^x$ are in the same unit as the dependent variable $\Delta S_{i,t}^B$ (i.e., bps); their sign and statistical significance are unaffected by alternative scaling factors (e.g., different high-low ranges for X_t or the sample standard deviation of X_t).

Consistent with Remark 1, POMOs’ positive liquidity externalities are increasing in our proxies for marketwide information heterogeneity (i.e., decreasing in ρ) — $\overline{\Delta\Delta S_{i,t}^{B,x}}$, $\Delta\gamma_{i,CB}^x$, and $\Delta\alpha_{i,CB}^x$ are negative and statistically significant — in correspondence with both same-maturity ($I_t^{CB} = 1$) and any-maturity POMOs ($I_t^{CB} = 1$), for both on-the-run Treasury notes and bonds. For instance, Panel A of 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 broad-based proxy for marketwide dispersion of beliefs $X_t = SSDF_q$ is high decline by roughly 110% (of the baseline effect in Table 3) more — or about 0.185 bps more — than when $SSDF_q$ is low (i.e., mean significant $\Delta\alpha_{i,CB}^x/\alpha_{i,CB} = 1.10$). Panel A of 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 nearly 2 bps lower than when $SSDF_q$ is low (i.e., $\overline{\Delta\Delta S_{i,t}^{B,x}} = -1.537$, $\Delta\gamma_{i,CB}^x = -1.897$, and $\Delta\alpha_{i,CB}^x = -1.664$). Those estimates are qualitatively similar, albeit smaller and less often statistically significant, when obtained from the dispersion of Nonfarm Payroll forecasts alone (i.e., when $X_t = SSDNFP_m$) in Panel B of Table 5. 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.

4.3.2 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 use two proxies for σ_v^2 . The first one is $EURVOL_m$ (plotted in Figure 4c), the monthly average (to smooth daily variability) of daily

Eurodollar implied volatility from Bloomberg. The second one is $TOVOL_m$ (in Figure 4d), the monthly average of daily realizations of the yield curve-weighted MOVE index of the normalized implied volatility on one-month Treasury options from Merrill Lynch. Both $EURVOL_m$ and $TOVOL_m$ are commonly used as measures of market participants’ perceived uncertainty surrounding U.S. macroeconomic fundamentals (e.g., Bernanke and Kuttner, 2005; Pasquariello and Vega, 2009). We then run the same univariate and multiple regressions for spread change differentials described in Section 4.3.1 — which yield scaled estimates $\overline{\Delta\Delta S_{i,t}^{B,x}}$ for the former, $\Delta\gamma_{i,CB}^x$ and $\Delta\alpha_{i,CB}^x$ for the latter — after imposing that either $X_t = EURVOL_m$ or $X_t = TOVOL_m$. We report these estimates in Panels A and B of Table 6, respectively.

Consistent with Remark 1, $\overline{\Delta\Delta S_{i,t}^{B,x}}$, $\Delta\gamma_{i,CB}^x$, and $\Delta\alpha_{i,CB}^x$ are always negative in Table 6, and nearly always statistically significant when proxying for fundamental uncertainty with $X_t = TOVOL_m$. For example, Panel B of Table 6 shows that during any-maturity POMO days when $TOVOL_m$ is historically high, the bid-ask spreads for ten-year Treasury notes decline by roughly 0.3 bps more than when $TOVOL_m$ is low (i.e., a statistically significant $\overline{\Delta\Delta S_{i,t}^{B,x}} = -0.309$, $\Delta\gamma_{i,CB}^x = -0.271$, and $\Delta\alpha_{i,CB}^x = -0.295$). This effect is economically significant as well, for it amounts to roughly 32% of the sample standard deviation of $\Delta S_{i,t}^B$ in Table 1. Those estimates are rarely statistically significant for $X_t = EURVOL_m$, in Panel A of Table 6. Yet, in those circumstances bid-ask spreads tighten much more pronouncedly on POMO days characterized by higher Eurodollar volatility — e.g., by no less than 100% of the baseline decline in spread reported in Table 3. This evidence suggests that government interventions are accompanied by a greater improvement in Treasury market liquidity when fundamental uncertainty is greater, as implied by our model.

4.3.3 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 informed speculators.

As discussed in Sections 2.2 and 3.2, the FRBNY’s Desk targets the aggregate level of non-borrowed reserves available in the banking system via uninformative POMOs to ensure that conditions in the federal funds rate market are “consistent” with the publicly known target

rate set by the FOMC.³³ Thus, uncertainty among market participants about the FRBNY’s non-public and uninformative reserve target for POMO days may manifest itself in the federal funds market. Accordingly, we measure marketwide policy uncertainty surrounding the Desk’s POMO days with $FEDVOL_m$ (plotted in Figure 4e), the monthly average (to smooth daily variability) of daily standard deviation of the federal funds rate, from the FRBNY.³⁴ Importantly, $FEDVOL_m$ is virtually unrelated to our proxies for marketwide dispersion of beliefs (ρ) and uncertainty (σ_v^2) about U.S. macroeconomic fundamentals described in Section 4.3.1 and 4.3.2. We then assess the sensitivity of spread changes in correspondence with POMO days to $X_t = FEDVOL_m$ by means of the same univariate and multiple regressions of Section 4.3.1.

Both sets of tests, in Table 7, provide further support for our model. As postulated by Remark 1, once again the resulting scaled estimates $\overline{\Delta\Delta S_{i,t}^{B,x}}$, $\Delta\gamma_{i,CB}^x$, and $\Delta\alpha_{i,CB}^x$ are negative for most maturities and in correspondence with both same-maturity ($I_{i,t}^{CB} = 1$) and any-maturity POMO days ($I_t^{CB} = 1$). Hence, these estimates suggest that liquidity improves more pronouncedly on POMO days when uncertainty about the Desk’s policy (proxied by $FEDVOL_m$) is greater. This effect is especially strong for thirty-year Treasury bonds. According to Table 7, those bonds’ bid-ask price spreads on same-maturity POMO days when $FEDVOL_m$ is historically high are about 1.7 bps ($\overline{\Delta\Delta S_{i,t}^{B,x}} = -1.657$ and $\Delta\alpha_{i,CB}^x = -1.740$, or about 20% of its sample mean in Table 1) lower than when $FEDVOL_m$ is low. Table 7 also shows that, when negative and statistically significant, the estimated slope and cross-product coefficients $\Delta\gamma_{i,CB}^x$ and $\Delta\alpha_{i,CB}^x$ for Treasury securities of shorter maturity are also large — e.g., ranging between 14% and 63% of the baseline estimated decline of their bid-ask spreads on any-maturity POMO days in Table 3 (i.e., of $\gamma_{i,CB}$ and $\alpha_{i,CB}$ of Eqs. (8) and (9), respectively).

In short, the evidence in Tables 5 to 7 indicates that the Treasury market’s information environment importantly affects the impact of government interventions on its process of price formation, 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

³³For 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].”

³⁴This data is available at <http://www.newyorkfed.org/markets/omo/dmm/fedfundsdata.cfm>.

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 monetary policy stance set and publicly announced by the Federal Open Market Committee (FOMC). To guide our analysis, we construct a parsimonious model of trading in the Treasury market in which — consistent with much recent empirical evidence (e.g., Brand and Kavaiecz, 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 unformativeness of its non-public target). Second, the extent of this improvement is sensitive to the market’s information environment.

Our subsequent empirical analysis of a comprehensive sample of price formation and FRBNY trades in the secondary U.S. Treasury market during the 2000s 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 information environment of the targeted markets. 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 ,

$$E[p_1|\delta_v(m)] = A_0 + A_1x(m) + A_1B_0(M-1) + A_1B_1(M-1)\rho\delta_v(m). \quad (\text{A-1})$$

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

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

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

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

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

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

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

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

$$A_0 = p_0 - MA_1B_0 \quad (\text{A-6})$$

$$A_1 = \frac{MB_1\rho\sigma_v^2}{MB_1^2\rho\sigma_v^2[1 + (M-1)\rho] + \sigma_z^2}. \quad (\text{A-7})$$

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

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

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 $A_1 > 0$. Since $E[\delta_{CB} | \delta_v(m)] = \psi \delta_v(m)$ and $E[\delta_v(m) | \delta_{CB}] = \rho \delta_{CB}$, the above expressions and the definition of ω_1 imply that, for each speculator m and the Central Bank,

$$E[p_1 | \delta_v(m)] = A_0 + A_1 x(m) + A_1 B_0 (M-1) + A_1 B_1 (M-1) \rho \delta_v(m) + A_1 C_0 + A_1 C_1 \psi \delta_v(m), \quad (\text{A-9})$$

$$E[p_1 | \delta_{CB}, \delta_T] = A_0 + A_1 x_{CB} + M A_1 B_0 + M A_1 B_1 \rho \delta_{CB}, \quad (\text{A-10})$$

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

$$p_0 + \delta_v(m) - A_0 - 2A_1 x(m) - (M-1) A_1 B_0 - (M-1) A_1 B_1 \rho \delta_v(m) - A_1 C_0 - A_1 C_1 \psi \delta_v(m) = 0. \quad (\text{A-11})$$

The second order condition is satisfied as $-2A_1 < 0$. For Eq. (A-11) to be true, it must be that

$$p_0 - A_0 = (M+1) A_1 B_0 + A_1 C_0, \quad (\text{A-12})$$

$$2A_1 B_1 = 1 - (M-1) A_1 B_1 \rho - A_1 C_1 \psi. \quad (\text{A-13})$$

The distributional assumptions of Sections 2.1 and 2.2 imply that

$$\begin{aligned} \arg \min_{x_{CB}} E[L | \delta_{CB}, \delta_T] &= \arg \min_{x_{CB}} [\gamma A_1^2 x_{CB}^2 + 2\gamma A_1^2 M B_0 x_{CB} \\ &+ 2\gamma A_1^2 M B_0 \rho \delta_{CB} x_{CB} + 2\gamma A_0 A_1 x_{CB} - 2\gamma p_T A_1 x_{CB} + (1-\gamma) A_0 x_{CB} \\ &+ (1-\gamma) A_1 x_{CB}^2 + (1-\gamma) M A_1 B_0 x_{CB} + (1-\gamma) M A_1 B_1 \rho \delta_{CB} x_{CB} \\ &- (1-\gamma) p_0 x_{CB} - (1-\gamma) \delta_{CB} x_{CB}]. \end{aligned} \quad (\text{A-14})$$

The first order condition of this minimization is then given by

$$\begin{aligned}
& 2\gamma A_1^2 x_{CB} + 2\gamma A_1^2 MB_0 + 2\gamma A_1^2 MB_0 \rho \delta_{CB} + 2\gamma A_0 A_1 - 2\gamma \bar{p}_T A_1 \\
& + (1 - \gamma) A_0 + 2(1 - \gamma) A_1 x_{CB} + (1 - \gamma) MA_1 B_0 \\
& + (1 - \gamma) MA_1 B_1 \rho \delta_{CB} - (1 - \gamma) p_0 - (1 - \gamma) \delta_{CB} = 0.
\end{aligned} \tag{A-15}$$

The second order condition is also satisfied as $2\gamma A_1^2 + 2(1 - \gamma) A_1 > 0$. Eq. (A-15) and $d \equiv \frac{\gamma}{1-\gamma}$ imply that

$$p_0 - A_0 = 2A_1 C_0 + MA_1 B_0 + 2dA_1^2 C_0 + 2dA_1^2 MB_0 + 2dA_0 A_1 - 2d\bar{p}_T A_1, \tag{A-16}$$

$$2A_1 C_1 = 1 - MA_1 B_1 \rho - 2dA_1^2 C_1 - 2dA_1^2 MB_1 \rho, \tag{A-17}$$

$$A_1 C_2 = dA_1 - dA_1^2 C_2, \tag{A-18}$$

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 $E(\omega_1) = MB_0 + C_0$ and variance

$$var(\omega_1) = MB_1^2 \rho \sigma_v^2 [1 + (M - 1) \rho] + C_1^2 \psi \sigma_v^2 + 2MB_1 C_1 \psi \rho \sigma_v^2 + \sigma_z^2 + C_2^2 \sigma_T^2. \tag{A-19}$$

Since $cov(v, \omega_1) = MB_1 \rho \sigma_v^2 + C_1 \psi \sigma_v^2$ and $p_1 = E(v|\omega_1)$ in equilibrium (Condition 2), it follows that

$$p_1 = p_0 + \frac{(MB_1 \rho \sigma_v^2 + C_1 \psi \sigma_v^2)(\omega_1 - MB_0 - C_0)}{MB_1^2 \rho \sigma_v^2 [1 + (M - 1) \rho] + C_1^2 \psi \sigma_v^2 + 2MB_1 C_1 \psi \rho \sigma_v^2 + \sigma_z^2 + C_2^2 \sigma_T^2}. \tag{A-20}$$

Thus, our conjecture for p_1 yields

$$A_0 = p_0 - MA_1 B_0 - A_1 C_0, \tag{A-21}$$

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

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 $A_1 C_0 = p_0 - A_0$ from Eq. (A-12) and plugging it into Eq. (A-16) leads us to $A_0 = p_0 + 2dA_1(p_0 - \bar{p}_T)$ and $C_0 = 2d(\bar{p}_T - p_0)$. 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

$$B_1 = \frac{1 - A_1 C_1 \psi}{A_1 [2 + (M - 1) \rho]}, \tag{A-23}$$

$$C_1 = \frac{1 - MA_1 B_1 \rho (1 + 2dA_1)}{2A_1 (1 + dA_1)}, \tag{A-24}$$

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 $f(A_1) = 2[2 + (M-1)\rho](1 + dA_1) - M\psi\rho(1 + 2dA_1)$. 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 ,

$$g_6 A_1^6 + g_5 A_1^5 + g_4 A_1^4 + g_3 A_1^3 + g_2 A_1^2 + g_1 A_1 + g_0 = 0, \quad (\text{A-25})$$

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

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

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

$$g_2 = \sigma_z^2 M\rho [M\rho(2-\psi)^2 + 4(2-\rho)(2-\psi)] + \sigma_T^2 d^2 [M\rho(2-\psi) + 2(2-\rho)]^2 + \sigma_v^2 d^2 \{M\rho [4M\rho\psi(1-\psi) + \psi^2(7-4\rho) + 5\psi(4-\rho) - 24] + 5\psi\rho(4-\rho) - 20\psi\}, \quad (\text{A-28})$$

$$g_3 = 2\sigma_z^2 d M\rho \{M\rho [8 - \psi(10 - 3\psi)] + 2[16 - 5\psi(2-\rho) + 8\rho]\} + 2\sigma_v^2 d^3 \{4M^2\rho^2\psi(1-\psi) + 2M\rho [\psi^2(1-\rho) + \psi(5-2\rho) - 4] - \psi(2-\rho)^2\} + 4\sigma_T^2 d^3 \{M^2\rho^2 [2 - \psi(3-\psi)] + M\rho [8 - 3\psi(2-\rho) - 4\rho] + 2(2-\rho)^2\}, \quad (\text{A-29})$$

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

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

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

and that either $\text{sign}(g_3) = \text{sign}(g_2) = \text{sign}(g_1)$, $\text{sign}(g_4) = \text{sign}(g_3) = \text{sign}(g_2)$, or $\text{sign}(g_4) = \text{sign}(g_3)$ and $\text{sign}(g_2) = \text{sign}(g_1)$, 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. According to Abel's Impossibility Theorem, the polynomial of Eq. (A-25) cannot be solved with rational operations and finite root extractions. In the numerical examples of Figure 1, we find λ_{CB} using the three-stage algorithm proposed by Jenkins and Traub (1970a, b). Unfortunately, this algorithm does not always identify all roots of the polynomial of Eq. (A-25). Thus, those examples are based on exogenous parameter values such that λ_{CB} can be found. ■

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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 basic sample period (January 1, 2001 to December 31, 2007, in Panel A); *ii*) the earlier subsample (January 1, 2001 to December 31, 2004, in Panel B); *iii*) the later subsample (January 1, 2005 to December 31, 2007, in Panel C); and *iv*) the crisis sample (January 1, 2008 to December 31, 2009, in Panel D). Data for three-year notes is available only between May 7, 2003 and March 30, 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. $\Delta S_{i,t}^B \equiv S_{i,t} - S_{i,t}^B$, where $S_{i,t}^B$ 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.

Segment	N	$S_{i,t}$			$\Delta S_{i,t}^B$			$V_{i,t}$		
		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***

Table 1. (Continued)

Segment	N	$S_{i,t}$			$\Delta S_{i,t}^B$			$V_{i,t}$		
		μ	σ	$\rho(1)$	μ	σ	$\rho(1)$	μ	σ	$\rho(1)$
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***
Panel D: BrokerTec, 01/2008-12/2009										
Two-year	469	0.848	0.09	0.99***	-0.003	0.09	0.32***	\$31.350	\$16.47	0.93***
Three-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Five-year	469	1.019	0.21	0.98***	-0.006	0.19	0.51***	\$27.596	\$12.61	0.95***
Ten-year	469	1.959	0.46	0.98***	-0.005	0.42	0.50***	\$22.980	\$9.03	0.95***
Thirty-year	463	6.137	3.92	0.98***	-0.026***	2.44	0.79***	\$3.531	\$1.53	0.92***

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 basic sample period (January 1, 2001 to December 31, 2007, in Panel A); *ii*) the earlier subsample (January 1, 2001 to December 31, 2004, in Panel B); *iii*) the later subsample (January 1, 2005 to December 31, 2007, in Panel C); and *iv*) the crisis sample (January 1, 2008 to December 31, 2009, in Panel D). 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. \bar{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.

Segment	$POMO_{i,t}$															
	Panel A: 01/2001-12/2007			Panel B: 01/2001-12/2004			Panel C: 01/2005-12/2007			Panel D: 01/2008-12/2009						
	N	N_d	μ	σ	N	N_d	μ	σ	N	N_d	μ	σ				
Total	217	25	\$1.108	\$0.44	153	26	\$1.073	\$0.48	64	23	\$1.194	\$0.29	75	73	\$2.020	\$6.52
Two-year	162	23	\$1.152	\$0.51	117	24	\$1.136	\$0.55	45	21	\$1.194	\$0.40	35	69	-\$0.981	\$7.98
Three-year	120	20	\$0.852	\$0.39	80	19	\$0.734	\$0.34	40	22	\$1.088	\$0.38	40	63	\$2.687	\$4.86
Five-year	78	16	\$0.565	\$0.40	50	15	\$0.430	\$0.30	28	19	\$0.805	\$0.45	39	53	\$3.071	\$4.04
Ten-year	36	10	\$0.343	\$0.25	24	10	\$0.306	\$0.21	12	11	\$0.416	\$0.32	21	32	\$1.086	\$1.33
Thirty-year	32	15	\$0.390	\$0.24	23	16	\$0.375	\$0.17	9	13	\$0.428	\$0.38	16	49	\$1.856	\$1.03

Table 3. POMO 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 POMO 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 models:

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T}Trend_t + \gamma_{i,\Delta D}\Delta D_{i,t}^B + \gamma_{i,\Delta C}\Delta C_{i,t}^B + \varepsilon_{i,t}, \quad (8)$$

where $\Delta S_{i,t}^B$ is computed over POMO days, $Trend_t$ is a time-trend variable, $\Delta D_{i,t}^B \equiv D_{i,t} - D_{i,t}^B$, $\Delta C_{i,t}^B \equiv C_{i,t} - C_{i,t}^B$, $D_{i,t}$ 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; and

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

where $\Delta S_{i,t}^B$ is computed over all days and $Calendar_t$ is a vector of day-of-the-week, monthly, and year dummies, for both same-maturity ($I_t = I_{i,t}^{CB}$) and any-maturity POMOs ($I_t = I_t^{CB}$). Means and regression coefficients are estimated over the basic BrokerTec sample period (January 1, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and March 30, 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 $\alpha_{i,CB}$.

Segment	Same-maturity POMOs				Any-maturity POMOs			
	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	R_a^2	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	R_a^2
Two-year	-0.125***	-0.306***	157	8%	-0.130***	-0.314***	211	9%
Three-year	-0.046*	-0.115**	58	11%	-0.087***	-0.257***	102	11%
Five-year	-0.215**	-0.594***	75	8%	-0.248***	-0.579***	210	12%
Ten-year	-0.074	-0.002	33	9%	-0.366***	-0.776***	196	10%
Thirty-year	-0.591	-1.316	28	6%	-0.778***	-1.337***	200	7%

Table 4. POMOs and Market Liquidity: Robustness

This table reports means of daily bid-ask price spread changes $\Delta S_{i,t}^B$ (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 models, exclusively over POMO days:

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T}Trend_t + \gamma_{i,\Delta D}\Delta D_{i,t}^B + \gamma_{i,\Delta C}\Delta C_{i,t}^B + \varepsilon_{i,t}, \quad (8)$$

and over all trading day:

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

for both same-maturity ($I_t = I_{i,t}^{CB}$) and any-maturity POMOs ($I_t = I_t^{CB}$), as described in Table 3. Means and regression coefficients are estimated over *i*) the earlier BrokerTec subsample (January 1, 2001 to December 31, 2004, in Panel A); *ii*) the later BrokerTec subsample (January 3, 2005 to December 31, 2007, in Panel B); *iii*) the full GovPX sample period (January 1, 2001 to December 31, 2004, in Panel C); *iv*) the extended BrokerTec subsample (January 1, 2001 to December 31, 2009, in Panel D); the crisis BrokerTec subsample (January 1, 2008 to December 31, 2009) for *v*) POMO purchases (in Panel E); and *vi*) POMO sales (in Panel F); the basic BrokerTec sample period (January 1, 2001 to December 31, 2007) *vii*) when computing the basic pre-intervention level $S_{i,t}^B$ over the past five non-POMO days (in Panel G); after replacing $\Delta S_{i,t}^B$ with $\Delta S_{i,t}^{B*} \equiv S_{i,t}^* - S_{i,t}^{B*}$, where $S_{i,t}^*$ and $S_{i,t}^{B*}$ are means of bid-ask price spreads over the 90-minute Fed Time when POMO auctions are typically conducted (10:00 a.m. to 11:30 a.m. ET, in Panel H); or *ix*) $\Delta S_{i,t}^B \equiv s_{i,t} - s_{i,t}^B$, where $s_{i,t}$ and $s_{i,t}^B$ are daily means of percentage bid-ask spreads $s_i = (A_i - B_i) / [\frac{1}{2}(A_i + B_i)]$ (in Panel I); after augmenting Eq. (9) to include the additional control variables for Treasury market conditions described in Section 4.2.4 (changes in overnight repo specialness, bid-to-cover ratios and number of days since the latest on-the-run Treasury auction, number of days since the latest FOMC meeting, each day's position over the cyclical reserve maintenance period, TOMO amounts, and the dates of Nonfarm Payroll, Unemployment, Nominal GDP, CPI, Industrial Production, and Housing Starts announcements), yielding: *x*) $\alpha_{i,CB}$ for changes in average daily bid-ask price spreads ($\Delta S_{i,t}^B$ in Panel J); *xi*) $\alpha_{i,CB}^*$ for changes in Fed Time daily bid-ask price spreads ($\Delta S_{i,t}^{B*}$ in Panel K); and *xii*) $\alpha_{i,CB}^{\circ}$ for changes in average daily percentage bid-ask spreads ($\Delta s_{i,t}^B$ in Panel L). Data for three-year notes is available only between May 7, 2003 and March 30, 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 $\alpha_{i,CB}$.

Table 4. (Continued)

Segment	Same-maturity POMOs					Any-maturity POMOs						
	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N
Panel A: BrokerTec, 01/2001-12/2004												
Two-year	-0.172***	-0.373***	114	-0.116***	12%	973	-0.184***	-0.373***	149	-0.126***	14%	973
Three-year	-0.091**	-0.046**	24	0.035	20%	407	-0.183***	-0.336***	45	-0.027	21%	407
Five-year	-0.328***	-0.715***	49	-0.216**	14%	977	-0.350***	-0.673***	148	-0.212***	17%	977
Ten-year	-0.107	0.109	21	-0.036	14%	855	-0.533***	-0.816***	134	-0.377***	16%	855
Thirty-year	-0.821	-0.710	19	-0.348	9%	804	-1.096***	-1.000***	138	-0.671*	9%	804
Panel B: BrokerTec, 01/2005-12/2007												
Two-year	-0.0002	-0.0005	43	0.0001	12%	709	-0.0003	-0.0005	62	-0.0004	11%	709
Three-year	-0.014***	-0.011***	34	-0.007	22%	557	-0.011***	-0.009***	57	-0.004	23%	557
Five-year	-0.003	-0.003	26	-0.003	23%	709	-0.003*	-0.003*	62	-0.004	23%	709
Ten-year	-0.017**	-0.016***	12	-0.007	15%	708	-0.004	-0.005	62	-0.004	14%	708
Thirty-year	-0.107*	-0.125*	9	-0.093**	16%	712	-0.069***	-0.074***	62	-0.049*	17%	712
Panel C: GovPX, 01/2001-12/2004												
Two-year	-0.208***	-0.306***	117	-0.159***	8%	984	-0.209***	-0.213***	153	-0.173***	9%	984
Three-year	-0.312	-0.004	23	-0.299	13%	345	-0.504*	-0.453	44	-0.510*	15%	345
Five-year	-0.061	-0.373***	49	-0.013	3%	939	-0.307***	-0.314***	152	-0.243**	4%	939
Ten-year	-0.349	-0.362	22	-0.237	3%	848	-0.490**	-0.390	148	-0.421**	4%	848
Thirty-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 4. (Continued)

Segment	Same-maturity POMOs				Any-maturity POMOs							
	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N
Panel D: BrokerTec, 01/2001-12/2009												
Two-year	-0.104***	-0.257***	189	-0.071***	7%	2,151	-0.099***	-0.255***	282	-0.066***	8%	2,151
Three-year	-0.046*	-0.115**	58	0.013	11%	964	-0.087***	-0.257***	102	-0.023	11%	964
Five-year	-0.151**	-0.466***	113	-0.085*	8%	2,157	-0.192***	-0.472***	281	-0.109***	11%	2,155
Ten-year	-0.056	-0.016	53	0.061	8%	2,034	-0.275***	-0.663***	267	-0.170**	9%	2,032
Thirty-year	-0.538	-1.040	43	-0.064	11%	1,981	-0.660**	-1.144***	270	-0.293	12%	1,979
Panel E: BrokerTec, 01/2008-12/2009, POMO purchases												
Two-year	-0.007	-0.007	19	0.001	1%	469	-0.009***	-0.010***	56	-0.015	12%	469
Three-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Five-year	-0.023***	-0.029***	32	-0.001	3%	471	-0.027***	-0.034***	56	-0.038*	21%	469
Ten-year	-0.026**	-0.012	19	0.012	0%	471	-0.030***	-0.022	56	-0.135*	23%	469
Thirty-year	-0.439***	-0.312**	15	-0.144	22%	465	-0.454***	-0.256***	56	-0.850**	48%	469
Panel F: BrokerTec, 01/2008-12/2009, POMO sales												
Two-year	0.001	-0.003	13	0.013	1%	469	-0.002	-0.006	15	-0.010	12%	469
Three-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Five-year	-0.022	-0.014	6	0.016	3%	471	-0.023*	-0.018	15	-0.041**	21%	469
Ten-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-0.011	-0.004	15	-0.097	22%	469
Thirty-year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	-0.190	-0.310	14	-0.406	47%	469

Table 4. (Continued)

Same-maturity POMOs						Any-maturity POMOs						
Segment	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N
Panel G: BrokerTec, 01/2001-12/2007, five-day benchmark window												
Two-year	-0.110***	-0.267***	157	-0.084***	5%	1,682	-0.110***	-0.263***	211	-0.083***	5%	1,682
Three-year	-0.034*	-0.062*	58	-0.008	5%	964	-0.065***	-0.193***	102	-0.039**	5%	964
Five-year	-0.248***	-0.635***	75	-0.198***	6%	1,686	-0.225***	-0.510***	210	-0.160***	7%	1,686
Ten-year	-0.111	-0.785	33	-0.075	3%	1,563	-0.270**	-0.581***	196	-0.188**	4%	1,563
Thirty-year	-0.381	-0.116	28	-0.120	2%	1,516	-0.662***	-1.239***	200	-0.518**	3%	1,516
Segment	$\overline{\Delta S_{i,t}^{B*}}$	$\gamma_{i,CB}^*$	N	$\alpha_{i,CB}^*$	R_a^2	N	$\overline{\Delta S_{i,t}^{B*}}$	$\gamma_{i,CB}^*$	N	$\alpha_{i,CB}^*$	R_a^2	N
Panel H: BrokerTec, 01/2001-12/2007, Fed Time												
Two-year	-0.124***	-0.309***	157	-0.082**	5%	1,682	-0.115***	-0.285***	211	-0.072**	5%	1,682
Three-year	-0.036	-0.098	58	-0.010	6%	964	-0.058***	-0.177***	102	-0.009	6%	964
Five-year	-0.213	-0.607**	75	-0.149	4%	1,686	-0.249***	-0.607***	210	-0.154***	7%	1,686
Ten-year	-0.099	-0.236	33	-0.019	4%	1,563	-0.349**	-0.819***	196	-0.246**	5%	1,563
Thirty-year	-0.216	-0.380	28	-0.004	2%	1,516	-1.021***	-1.820***	200	-0.840**	3%	1,516
Segment	$\overline{\Delta s_{i,t}^B}$	$\alpha_{i,CB}^s$	N	$\alpha_{i,CB}^s$	R_a^2	N	$\overline{\Delta s_{i,t}^B}$	$\alpha_{i,CB}^s$	N	$\alpha_{i,CB}^s$	R_a^2	N
Panel I: BrokerTec, 01/2001-12/2007, percentage spread												
Two-year	-0.124***	-0.305***	157	-0.085***	8%	1,682	-0.129***	-0.313***	211	-0.089***	9%	1,682
Three-year	-0.046**	-0.114**	58	0.013	11%	964	-0.088***	-0.254***	102	-0.023	11%	964
Five-year	-0.205***	-0.574***	75	-0.137*	8%	1,686	-0.239***	-0.564***	210	-0.148***	12%	1,686
Ten-year	-0.059	0.067	33	0.040	9%	1,563	-0.349***	-0.728***	196	-0.251***	10%	1,563
Thirty-year	-0.524	-1.169	28	-0.267	6%	1,516	-0.642***	-0.995***	200	-0.471*	6%	1,516

Table 4. (Continued)

Same-maturity POMOs						Any-maturity POMOs						
Segment	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}$	N	$\alpha_{i,CB}$	R_a^2	N
Panel J: BrokerTec, 01/2001-12/2007, with controls												
Two-year	n.a.	-0.777***	157	-0.079***	10%	1,682	n.a.	-0.675***	211	-0.081***	11%	1,682
Three-year	n.a.	-0.380*	58	0.014	16%	964	n.a.	-0.205*	102	-0.019	17%	964
Five-year	n.a.	-1.375*	75	-0.117*	10%	1,686	n.a.	-0.830***	210	-0.134***	13%	1,686
Ten-year	n.a.	-0.690	33	0.064	10%	1,563	n.a.	-0.944**	196	-0.251***	11%	1,563
Thirty-year	n.a.	-0.582	28	-0.234	7%	1,516	n.a.	-0.670*	200	-0.516**	9%	1,516
Segment	$\overline{\Delta S_{i,t}^{B*}}$	$\gamma_{i,CB}^*$	N	$\alpha_{i,CB}^*$	R_a^2	N	$\overline{\Delta S_{i,t}^{B*}}$	$\gamma_{i,CB}^*$	N	$\alpha_{i,CB}^*$	R_a^2	N
Panel K: BrokerTec, 01/2001-12/2007, Fed Time, with controls												
Two-year	n.a.	-0.835***	157	-0.079**	6%	1,682	n.a.	-0.629***	211	-0.066**	6%	1,682
Three-year	n.a.	-0.468*	58	-0.116	13%	964	n.a.	-0.567***	102	-0.016	13%	964
Five-year	n.a.	-1.458	75	-0.131	5%	1,686	n.a.	-0.927**	210	-0.149***	8%	1,686
Ten-year	n.a.	-0.090	33	0.047	4%	1,563	n.a.	-1.187*	196	-0.246*	6%	1,563
Thirty-year	n.a.	-0.603	28	-0.547	2%	1,516	n.a.	-0.436**	200	-0.854**	4%	1,516
Segment	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}^s$	N	$\alpha_{i,CB}^s$	R_a^2	N	$\overline{\Delta S_{i,t}^B}$	$\gamma_{i,CB}^s$	N	$\alpha_{i,CB}^s$	R_a^2	N
Panel L: BrokerTec, 01/2001-12/2007, percentage spread, with controls												
Two-year	n.a.	-0.766***	157	-0.079***	10%	1,682	n.a.	-0.665***	211	-0.081***	11%	1,682
Three-year	n.a.	-0.035*	58	0.013	16%	964	n.a.	-0.209*	102	-0.019	18%	964
Five-year	n.a.	-1.301**	75	-0.113*	9%	1,686	n.a.	-0.765***	210	-0.132***	13%	1,686
Ten-year	n.a.	-0.808	33	0.077	10%	1,563	n.a.	-0.788***	196	-0.241***	11%	1,563
Thirty-year	n.a.	-0.495	28	-0.203	7%	1,516	n.a.	-0.367*	200	-0.444**	9%	1,516

Table 5. POMO and Information Heterogeneity

This table reports OLS slope coefficients $\beta_{i,CB}^x$ of the following regression of average daily bid-ask spread and price changes $\Delta S_{i,t}^B$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (i) over *same*-maturity or *any*-maturity POMO days ($I_{i,t}^{CB} = 1$ or $I_t^{CB} = 1$) on the contemporaneous realizations of either $X_t = SSDF_q$ (the simple scaled average of the standardized dispersion of analyst forecasts of six macroeconomic variables from SPF, see Section 4.3.1; in Panel A) or $X_t = SSDNF_m$ (the scaled standardized dispersion of analyst forecasts of Nonfarm Payroll from Bloomberg, see Section 4.3.1; in Panel B) multiplied by the difference between $X_t^{70^{th}}$ (the top 70th percentile of its empirical distribution) and $X_t^{30^{th}}$ (the bottom 30th percentile of its empirical distribution):

$$\Delta S_{i,t}^B = \beta_{i,CB} + \beta_{i,CB}^x X_t + \varepsilon_{i,t}. \quad (10)$$

We label these differences as $\overline{\Delta S_{i,t}^{B,x}} = \beta_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$. We also estimate, again by OLS, both the effect of either $X_t = SSDF_q$ or $X_t = SSDNF_m$ on $\Delta S_{i,t}^B$ in event time (slope $\gamma_{i,CB}^x$):

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T} Trend_t + \gamma_{i,\Delta D} \Delta D_{i,t}^B + \gamma_{i,\Delta C} \Delta C_{i,t}^B + \gamma_{i,CB}^x X_t + \varepsilon_{i,t}, \quad (11)$$

as well as the interaction of either $I_t = I_{i,t}^{CB}$ or $I_t = I_t^{CB}$ with either $X_t = SSDF_q$ or $X_t = SSDNF_m$ over the full sample (interaction $\alpha_{i,CB}^x$):

$$\Delta S_{i,t}^B = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,x} X_t + \alpha_{i,CB} I_t + \alpha_{i,CB}^x I_t X_t + \varepsilon_{i,t}. \quad (12)$$

We report these slope and interaction coefficients as $\Delta \gamma_{i,CB}^x = \gamma_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$ and $\Delta \alpha_{i,CB}^x = \alpha_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$, again in bps. Means and regression coefficients are estimated over the basic sample period (January 1, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and March 30, 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 $\alpha_{i,CB}^x$.

Table 5. (Continued)

Segment	Same-maturity POMOs					Any-maturity POMOs						
	$\Delta\Delta S_{i,t}^{B,x}$	$\Delta\gamma_{i,CB}^x$	N	$\Delta\alpha_{i,CB}^x$	R_a^2	N	$\Delta\Delta S_{i,t}^{B,x}$	$\Delta\gamma_{i,CB}^x$	N	$\Delta\alpha_{i,CB}^x$	R_a^2	N
Panel A: $X_t = SSDF_q$												
Two-year	-0.099***	-0.061***	157	-0.086***	9%	1,682	-0.107***	-0.067***	211	-0.092***	11%	1,682
Three-year	0.011	0.003	58	0.014	10%	964	-0.023	-0.047**	102	-0.017	11%	964
Five-year	-0.220***	-0.150	75	-0.172	9%	1,686	-0.206***	-0.137***	210	-0.167***	13%	1,686
Ten-year	-0.274*	-0.461*	33	-0.297*	9%	1,563	-0.361***	-0.248***	196	-0.295***	11%	1,563
Thirty-year	-1.537**	-1.897*	28	-1.664**	7%	1,516	-0.247	-0.051	200	-0.373	7%	1,516
Panel B: $X_t = SSDNF_m$												
Two-year	-0.064***	-0.065***	157	-0.056**	9%	1,682	-0.068***	-0.015**	211	-0.058**	10%	1,682
Three-year	0.002	0.008	58	0.006	11%	964	-0.008	-0.028*	102	0.018	11%	964
Five-year	0.080	0.096	75	0.059	9%	1,686	-0.074*	-0.051	210	-0.062	12%	1,686
Ten-year	-0.337*	-0.329	33	-0.282	9%	1,563	-0.117**	-0.011	196	-0.118**	10%	1,563
Thirty-year	-0.425	-0.541	28	-0.223	6%	1,516	-0.098	-0.069	200	0.075	7%	1,516

Table 6. POMO and Fundamental Uncertainty

This table reports OLS slope coefficients $\beta_{i,CB}^x$ of the following regression of average daily bid-ask spread and price changes $\Delta S_{i,t}^B$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (i) over *same*-maturity or *any*-maturity POMO days ($I_{i,t}^{CB} = 1$ or $I_t^{CB} = 1$) on the contemporaneous realizations of either $X_t = EURVOL_m$ (the monthly average of daily Eurodollar implied volatility from Bloomberg, see Section 4.3.2; in Panel A) or $X_t = TOVOL_m$ (the monthly average of daily implied volatility on Treasury options from Merrill Lynch, see Section 4.3.2; in Panel B) multiplied by the difference between $X_t^{70^{th}}$ (the top 70th percentile of its empirical distribution) and $X_t^{30^{th}}$ (the bottom 30th percentile of its empirical distribution):

$$\Delta S_{i,t}^B = \beta_{i,CB} + \beta_{i,CB}^x X_t + \varepsilon_{i,t}. \quad (10)$$

We label these differences as $\overline{\Delta \Delta S_{i,t}^{B,x}} = \beta_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$. We also estimate, again by OLS, both the effect of either $X_t = EURVOL_m$ or $X_t = TOVOL_m$ on $\Delta S_{i,t}^B$ in event time (slope $\gamma_{i,CB}^x$):

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T} Trend_t + \gamma_{i,\Delta D} \Delta D_{i,t}^B + \gamma_{i,\Delta C} \Delta C_{i,t}^B + \gamma_{i,CB}^x X_t + \varepsilon_{i,t}, \quad (11)$$

as well as the interaction of either $I_t = I_t^{CB}$ or $I_t = I_t^{CB}$ with either $X_t = EURVOL_m$ or $X_t = TOVOL_m$ over the full sample (interaction $\alpha_{i,CB}^x$):

$$\Delta S_{i,t}^B = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,x} X_t + \alpha_{i,CB} I_t + \alpha_{i,CB}^x I_t X_t + \varepsilon_{i,t}. \quad (12)$$

We report these slope and interaction coefficients as $\Delta \gamma_{i,CB}^x = \gamma_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$ and $\Delta \alpha_{i,CB}^x = \alpha_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$, again in bps. Means and regression coefficients are estimated over the basic sample period (January 1, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and March 30, 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 $\alpha_{i,CB}^x$.

Table 6. (Continued)

Segment	Same-maturity POMOs					Any-maturity POMOs						
	$\Delta\Delta S_{i,t}^{B,x}$	$\Delta\gamma_{i,CB}^x$	N	$\Delta\alpha_{i,CB}^x$	R_a^2	N	$\Delta\Delta S_{i,t}^{B,x}$	$\Delta\gamma_{i,CB}^x$	N	$\Delta\alpha_{i,CB}^x$	R_a^2	N
Panel A: $X_t = EURVOL_m$												
Two-year	-0.015	-0.091***	157	-0.027	9%	1,682	-0.026	-0.076***	211	-0.034	10%	1,682
Three-year	-0.051*	-0.008	58	-0.025	10%	964	-0.130***	0.024	102	-0.086**	11%	964
Five-year	-0.039	-0.154	75	-0.060	9%	1,686	-0.023	-0.182***	210	-0.049	13%	1,686
Ten-year	-0.398	-0.513	33	-0.323***	9%	1,563	-0.123	0.192	196	-0.154**	11%	1,563
Thirty-year	-0.898	-1.171	28	-0.479	7%	1,516	-0.452	-0.246	200	-0.340	8%	1,516
Panel B: $X_t = TOVOL_m$												
Two-year	-0.102***	-0.107***	157	-0.093***	9%	1,682	-0.117***	-0.123***	211	-0.102***	10%	1,682
Three-year	-0.076**	-0.069*	58	-0.049	11%	964	-0.159***	-0.150***	102	-0.126***	12%	964
Five-year	-0.198*	-0.206*	75	-0.176**	9%	1,686	-0.185***	-0.176**	210	-0.147***	12%	1,686
Ten-year	-0.355	-0.301	33	-0.372***	9%	1,563	-0.309***	-0.271***	196	-0.295***	11%	1,563
Thirty-year	-1.500	-1.959	28	-0.1407**	6%	1,516	-0.584	-0.652*	200	-0.578**	7%	1,516

Table 7. POMOs and POMO Policy Uncertainty

This table reports OLS slope coefficients $\beta_{i,CB}^x$ of the following regression of average daily bid-ask spread and price changes $\Delta S_{i,t}^B$ (in bps, defined in Section 4.1) for on-the-run Treasury notes and bonds (\hat{v}) over *same*-maturity or *any*-maturity POMO days ($I_t^{CB} = 1$ or $I_t^{CB} = 1$) on the contemporaneous realizations of $FEDVOL_m$ — the monthly average of daily volatility of the federal funds rate, from the FRBNY, see Section 4.3.3 — multiplied by the difference between $FEDVOL_m^{70^{th}}$ (the top 70th percentile of its empirical distribution) and $FEDVOL_m^{30^{th}}$ (the bottom 30th percentile of its empirical distribution):

$$\Delta S_{i,t}^B = \beta_{i,CB} + \beta_{i,CB}^x X_t + \varepsilon_{i,t}. \quad (10)$$

We label these differences as $\overline{\Delta \Delta S_{i,t}^{B,x}} = \beta_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$. We also estimate, again by OLS, both the effect of $X_t = FEDVOL_m$ on $\Delta S_{i,t}^B$ in event time (slope $\gamma_{i,CB}^x$):

$$\Delta S_{i,t}^B = \gamma_{i,CB} + \gamma_{i,T} Trend_t + \gamma_{i,\Delta D} \Delta D_{i,t}^B + \gamma_{i,\Delta C} \Delta C_{i,t}^B + \gamma_{i,CB}^x X_t + \varepsilon_{i,t}, \quad (11)$$

as well as the interaction of either $I_t = I_t^{CB}$ or $I_t = I_t^{CB}$ with $X_t = FEDVOL_m$ over the full sample (interaction $\alpha_{i,CB}^x$):

$$\Delta S_{i,t}^B = \alpha_{i,0} + \alpha_{i,C} Calendar_t + \alpha_{i,\Delta D} \Delta D_{i,t}^B + \alpha_{i,\Delta C} \Delta C_{i,t}^B + \alpha_{i,x} X_t + \alpha_{i,CB} I_t + \alpha_{i,CB}^x I_t X_t + \varepsilon_{i,t}. \quad (12)$$

We report these slope and interaction coefficients as $\Delta \gamma_{i,CB}^x = \gamma_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$ and $\Delta \alpha_{i,CB}^x = \alpha_{i,CB}^x (X_t^{70^{th}} - X_t^{30^{th}})$, again in bps. Means and regression coefficients are estimated over the basic sample period (January 1, 2001 to December 31, 2007). Data for three-year notes is available only between May 7, 2003 and March 30, 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 $\alpha_{i,CB}^x$.

Segment	Same-maturity POMOs				Any-maturity POMOs							
	$\overline{\Delta \Delta S_{i,t}^{B,x}}$	$\Delta \gamma_{i,CB}^x$	N	R_a^2	$\overline{\Delta \Delta S_{i,t}^{B,x}}$	$\Delta \gamma_{i,CB}^x$	N	R_a^2				
Two-year	-0.061***	-0.062***	157	-0.046*	9%	1,682	-0.076***	-0.076***	211	-0.056**	10%	1,682
Three-year	0.048**	0.041	58	0.012	11%	964	0.082***	0.073***	102	0.044***	12%	964
Five-year	-0.183*	-0.174*	75	-0.157	9%	1,686	-0.094**	-0.083***	210	-0.055	12%	1,686
Ten-year	0.157	0.071	33	0.039	9%	1,563	-0.105**	-0.106***	196	-0.111***	10%	1,563
Thirty-year	-1.657*	-1.627	28	-1.740***	7%	1,516	0.012	0.004	200	-0.124	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 $M = 500$.

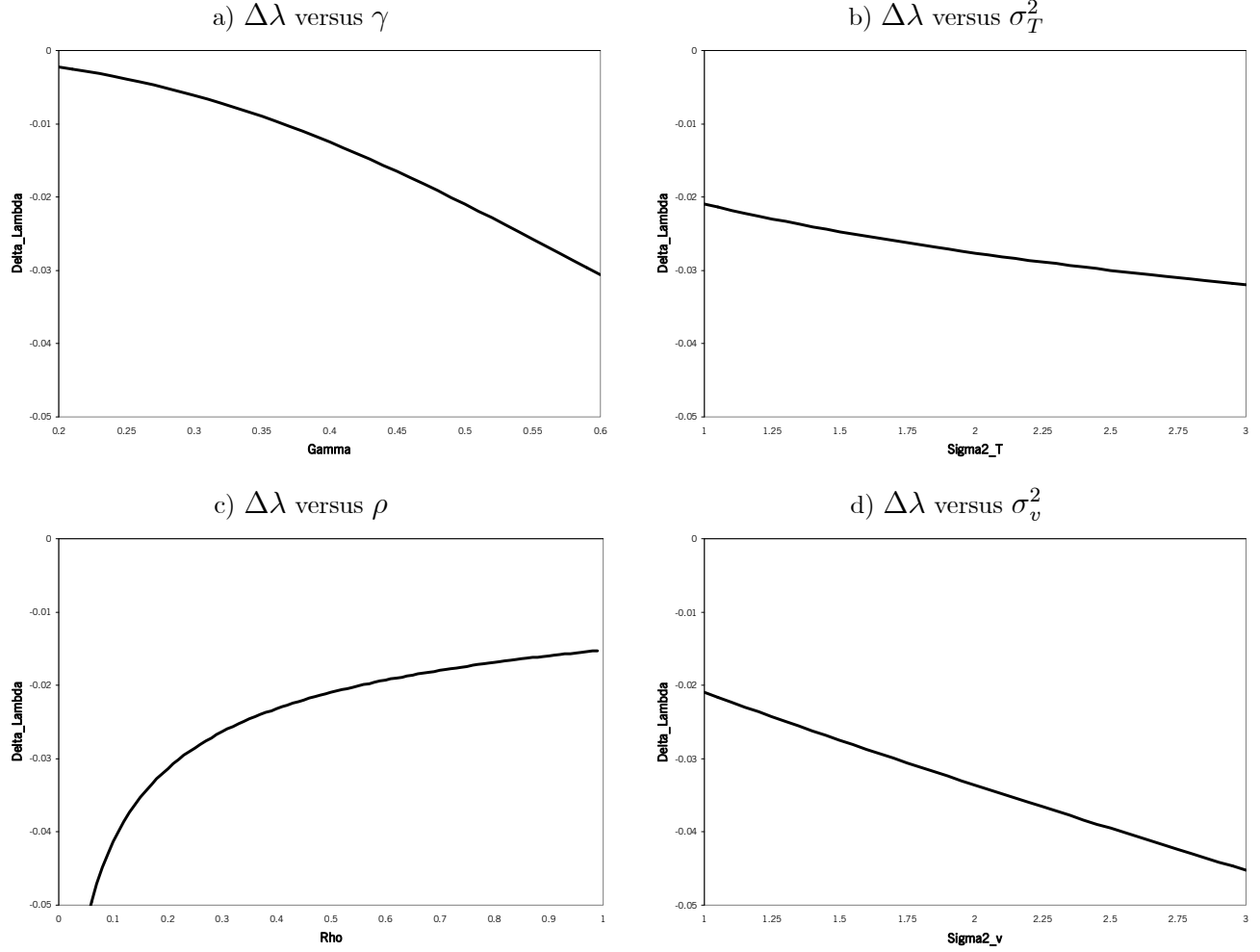


Figure 2. U.S. Treasury Notes and Bonds: Bid-Ask Spreads

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 1, 2001 and December 31, 2009. Data for three-year notes is available only between May 7, 2003 and March 30, 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.

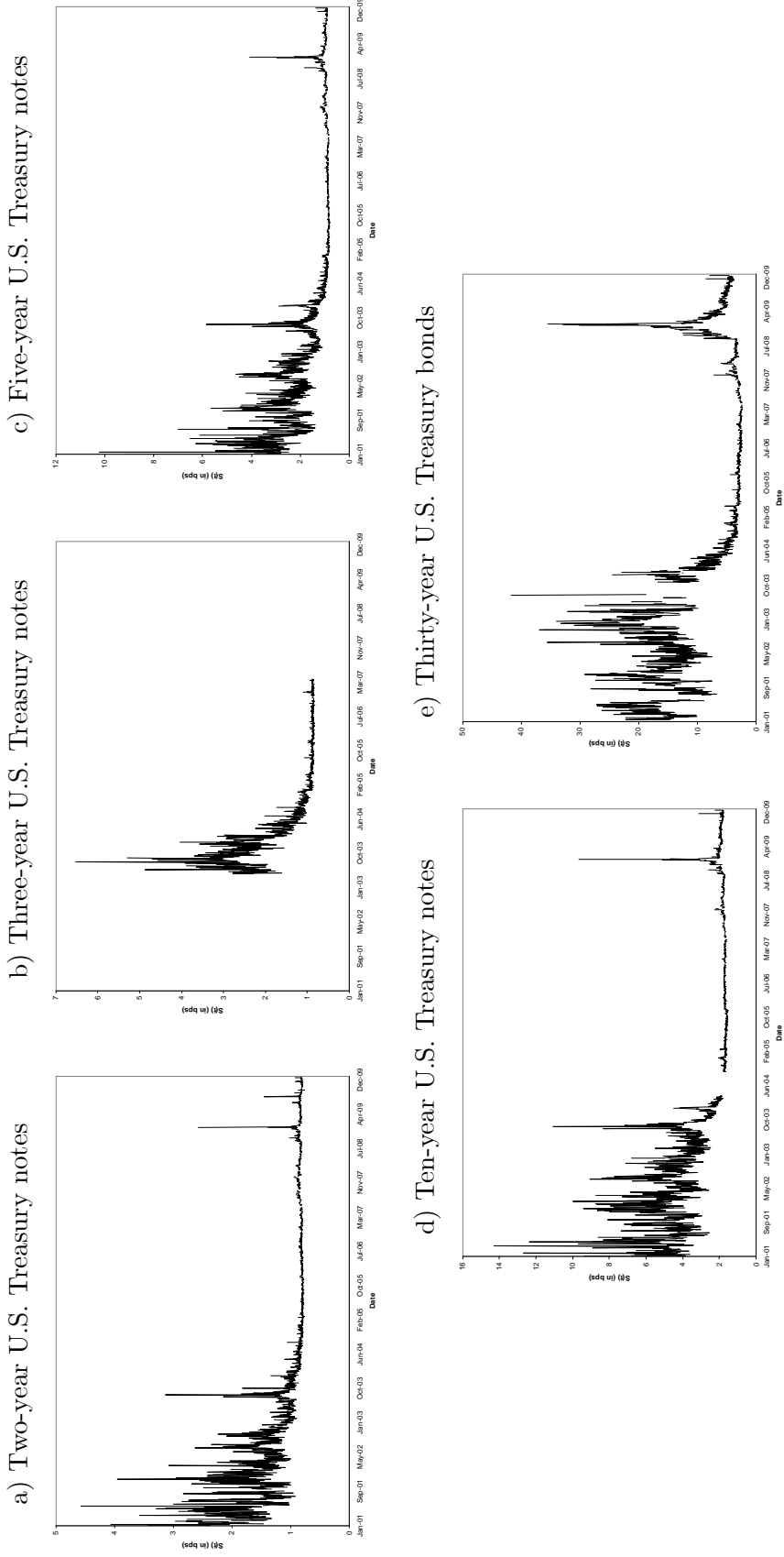


Figure 3. POMO and Federal Funds Rates

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 1, 2001 and December 31, 2009.

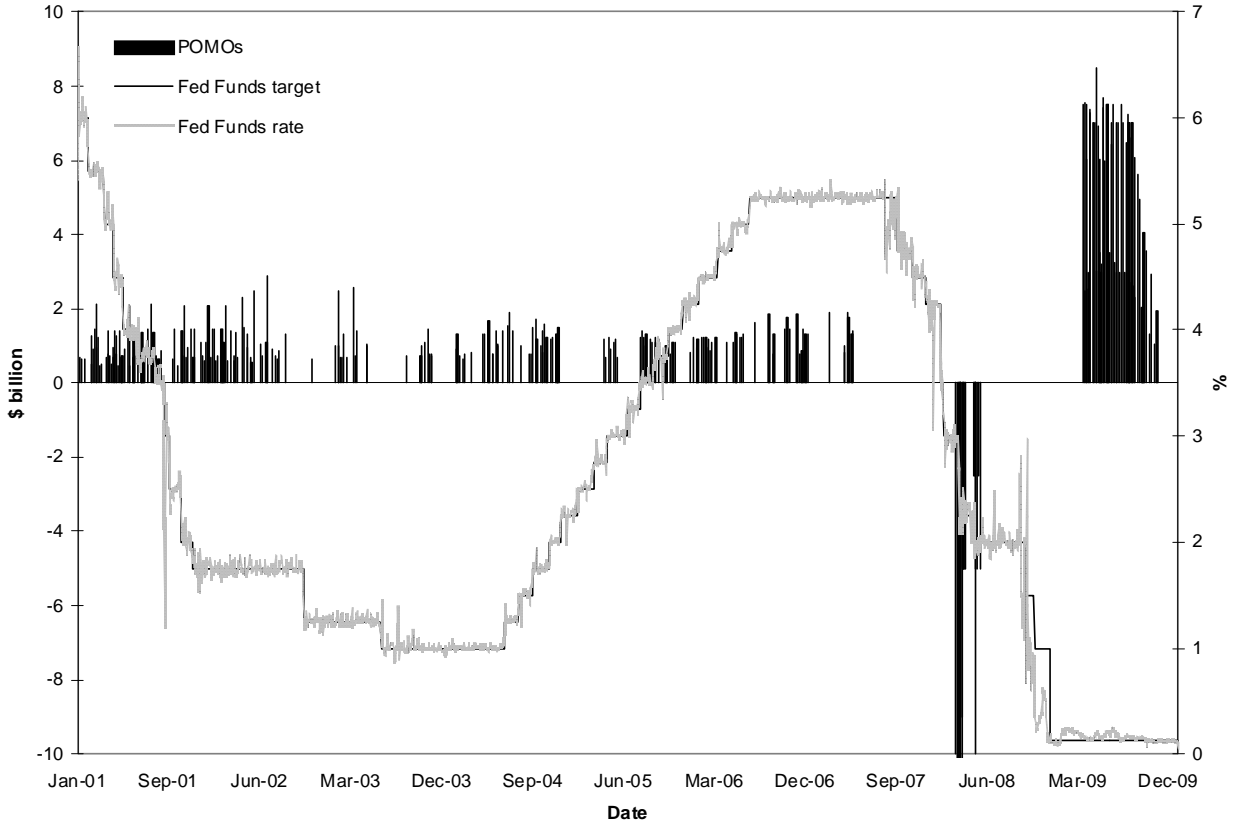


Figure 4. Marketwide Information Variables

This figure plots $SDDF_q$ (Figure 4a), the scaled simple average of standardized standard deviation of professional forecasts of six U.S. macroeconomic variables (Unemployment, Nonfarm Payroll, Nominal GDP, CPI, Industrial Production, Housing Starts) from SPF (Section 4.3.1); $SSDNF_m$ (Figure 4b), the scaled standardized standard deviation of professional forecasts of Nonfarm Payroll from Bloomberg (Section 4.3.1); $EURVOL_m$ (Figure 4c), the monthly average of daily Eurodollar implied volatility (in percentage) from Bloomberg (Section 4.3.2); $TOVOL_m$ (Figure 4d), the monthly average of daily implied volatility on one-month Treasury options from Merrill Lynch (Section 4.3.2); $FEDVOL_m$ (Figure 4e), the monthly average of daily implied volatility of the federal funds rate (in percentage) from FRBNY (Section 4.3.3), between January 2001 and December 2009.

