The Impact of Central Bank Communication Choices in a Market with Fast and Slow Traders*

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Abstract

We study the impact of different central bank communication practices on market liquidity, volatility and the trading behavior and profitability of fast and slow traders in the foreign exchange market. We find that the Bank of Japan's practice of introducing some randomness to the exact time of day at which it releases its monetary policy statement increases illiquidity and realized volatility well before the release time. This contrasts with what we observe for the Federal Reserve and the European Central Bank, which both release their monetary policy statements at fixed pre-announced times. We show that the additional uncertainty due to the random timing of the Bank of Japan's announcement gives an advantage to fast traders, especially when they trade aggressively against slower traders in the market. We relate our findings to the theory of market liquidity provision under adverse selection risk and to the discussion of how information asymmetry affects fast and slow traders in financial markets in which they coexist.

Keywords: Monetary policy, public information, high frequency traders, random release times, central bank and CEO communication.

JEL Classifications: C53, D83, E27, E37, E44, E47, E5, G1.

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1 Introduction

As major central banks around the world have become more transparent over time, policy makers and academics have been increasingly searching for effective central bank communication strategies. The literature on central bank communications has focused on the optimal level of transparency and on how to communicate information, principally through monetary policy statements, press conferences and speeches, with the goal to maximize the effectiveness of monetary policy. Despite the obvious impact of central bank communications on financial markets, the literature has so far paid little attention to how the specific ways in which central banks release their monetary policy decisions affect asset price volatility and market liquidity, and how they impact different types of market participants. These issues are particularly relevant because the financial markets which are most directly affected by central bank communications are now often populated by a mixture of fast and slow traders with varying abilities to absorb and react to new information.[1]

We focus in this paper on this aspect of central bank communications, as we analyze the impact of monetary policy announcements by the policy-making bodies of the Federal Reserve (Fed), the Eurosystem (ECB) and the Bank of Japan (BoJ) on market liquidity, volatility, and the trading behavior and profitability of fast and slow traders in the interdealer foreign exchange market, a market which is highly sensitive to monetary policy information. The three central banks we study have adopted different communication styles and, in particular, different methods by which they release information. While the Fed and the ECB release their monetary policy decisions at a fixed time known to the public in advance, the BoJ releases its decision a few minutes after the end of each monetary policy meeting. Thus, both by nature and by design, the BoJ's release time varies from meeting to meeting and is not known in advance.[2] We show that this difference matters. Specifically, the difference between the BoJ, Fed and ECB in the way monetary policy decisions are released to the public has a substantial impact on market quality up to several hours before each announcement.

[1]Fast traders are traders that use highly-automated low-latency trading technology, including automated textual analysis technology. Slow traders are traders that manually enter trade orders on a keyboard.

[2]The BoJ reportedly chose this method in 2001 in order to lower the risk of news leakage and thereby reduce the possibility of giving an information advantage to some market participants. In our sample period, October 2012 to December 2017, the release times of BoJ monetary policy statements fall within approximately a three hour window, from 11:40 a.m. to 2:46 p.m. Japan Standard Time (JST).

Our empirical analysis is guided by economic theory. Existing market microstructure models predict that illiquidity in a financial market should increase a few minutes before pre-scheduled public announcements (announcements made at a widely known date and time), as liquidity providers increase bid-ask spreads to be compensated for possible adverse selection costs and inventory management costs.[3] Thus, for ECB and Fed announcements, we expect illiquidity to rise shortly before the announcements. In contrast, for unscheduled public announcements (announcements whose release date and time has not been pre-announced) theory predicts that illiquidity should only increase after the announcements because, by definition, liquidity providers cannot forecast when these announcement will be released and therefore when adverse selection and inventory management costs may rise (see, for instance, Dugast, 2018).

The manner in which the BoJ releases its monetary policy decisions clearly does not fit perfectly either of these two types of announcements, as the dates of the monetary policy decisions are publicly known well in advance, but the precise release times of the announcements are unknown. We introduce this "hybrid" type of announcement into a standard microstructure model with asymmetric information (Glosten and Milgrom, 1985) and show analytically that this crucial difference implies that, on days when the BoJ releases its monetary policy decisions, bid-ask spreads should begin to increase as soon as market participants expect that information could be released at any moment. Bid-ask spreads should then continue to increase until the announcement is made as, until the actual release occurs, market participants assign an increasing probability to the event that an announcement will be made in the next period.

Consistent with these predictions, we indeed find that over our sample period BoJ monetary policy announcements are preceded by a period of elevated illiquidity that can last up to several hours, with bid-ask spreads gradually rising until the announcements are made. In contrast, for the monetary policy announcements of the Fed and ECB, bid-ask spreads begin to widen only a few minutes before the announcements. We also show that, for our three central banks, illiquidity typically remains elevated for up to 2 hours following monetary policy announcements, as the new information is incorporated into prices.

[3] A broad range of theoretical models lead to similar predictions, including models with informed traders (e.g., Glosten and Milgrom, 1985; Foucault et al., 2016; Dugast, 2018) and models where market makers demand compensation for carrying inventory (e.g. Tinic, 1972; Amihud and Mendelson, 1980; Ho and Stoll, 1983; O'Hara and Oldfield, 1986).

The expected effect of a random release time on market volatility is perhaps less clear. Broadly speaking, economic theory predicts that asset price volatility will be high when there is uncertainty or disagreement among market participants about the fundamental value of the asset, when information relevant to the asset's price has just been released, or when the market is not very liquid. In the case of the BoJ, while new relevant information is obviously not observed before its announcement, market liquidity is clearly affected. Therefore we expect volatility to increase prior to BoJ announcements, while it should not increase before the fixed-time ECB and Fed announcements, with the difference directly related to the BoJ's random release time.

Consistent with our expectations, we do observe that realized volatility tends to be elevated in the hour before the BoJ releases but we find no such effect on realized volatility in the hour prior to ECB and Fed announcements. From a policy perspective, this is an important finding because volatility purely due to illiquidity and not associated with price discovery is the type of volatility that market regulators and policy makers seek to avoid. The finding is also relevant within the context of the literature that studies the relationship between illiquidity and volatility, as it is a rare example of a financial market experiencing an increase in both illiquidity and volatility without the release of new information.

Focusing further on that relationship, we estimate the joint dynamics of intraday liquidity and volatility before and after the three central bank announcements, with the goal to discern the effect that the random release time of the BoJ announcement may have on the relationship between these two variables. We find that illiquidity has a larger and more persistent impact on volatility before BoJ announcements than before Fed announcements. In contrast, when comparing the Fed and ECB announcements, iliquidity clearly has a larger impact before Fed announcements. As we find that volatility also drives illiquidity, this suggests that the BoJ's random release time may boost the potentially destabilizing feedback relationship between the two variables, potentially contributing to even further illiquidity. In terms of the economic magnitude of the effects, we note that the effect that illiquidity has on volatility is larger than the effect that volatility has on illiquidity, consistent with the finding of Nguyen et al. (2020).

Finally we consider how the BoJ's random release time may affect the information asymmetry between fast and slow traders, which may then exacerbate the illiquidity (and resulting volatility) observed well before the announcements. As we will discuss, traders with varying technological abilities are active on the EBS platform during our sample period, ranging from high-frequency traders (HFTs) using highly-automated low-latency trading technology capabilities, including automated textual analysis technology, to traders that manually enter orders on a keyboard. For all three central bank releases, we expect that fast traders can process and react to the information content of the releases more quickly than slower traders. The speed advantage of the fast traders likely creates short periods of information advantage for these traders upon the release of information, effectively resulting in a form of temporary information asymmetry between fast and slow traders even when the information in question is released broadly to the public. This is discussed, for instance, by Haldane (2011) and O'Hara (2016), and also by Foucault et al. (2016) when they introduce the concept of *news trading*.

Above and beyond that, however, and in contrast to the cases of the Fed and ECB, the random time of the BoJ release likely creates an additional layer of information advantage between fast and slow traders as the slow traders do not know precisely when they will be most at risk of adverse selection. The higher risk of adverse selection by fast traders, in turn, may then exacerbate illiquidity, and therefore volatility, well ahead of the BoJ releases, as liquidity providers take additional protective measures. Indeed, our analysis shows that the random release time of the BoJ's announcement appears to give an additional advantage to HFTs. The evidence comes in the form of higher HFT trading profits immediately after the release of the BoJ's statement than in the cases of the Fed and ECB, particularly when HFTs trade aggressively against the liquidity provided by slower traders.

Our paper contributes to several strands of the literature. First, the paper contributes to the literature on central bank communication, and it suggests that the literature should expand in a new direction. There has been for many years an extensive literature on the optimal communication strategy of central banks (see, for instance, Blinder et al., 2008, for a review of the literature from the 1990s and 2000s). But, to the best of our knowledge, the literature on central bank communication has not focused on how specific communication practices may affect market quality and may benefit certain types of market participants more than others. Of course, from a narrow central bank policy implementation angle, our study strongly suggests that, if central banks seek to minimize their effect on asset price volatility, as in Stein and Sunderam (2018), releasing monetary policy decisions at a random time is not optimal. This is particularly important today with the existence of textual analysis and Artificial Intelligence technologies and investors that use these technologies to profit from an informational advantage.

Second, the paper contributes to the literature that discusses the effects of scheduled and unscheduled information releases on market liquidity and volatility. The literature has broadly used a binary classification, consisting, on one hand, of announcements for which the date and release times are fully known (see for example, Bollerslev et al., 2018; Nguyen et al., 2020), and on the other hand, of totally unscheduled announcements (see, e.g., Dugast, 2018). In contrast, we focus on a hybrid of these two types, announcements which occur on a pre-announced date but with a release time that is not known ahead of time, and we study the impact that this type of announcement has on the market before the release of the information.

Third, the paper contributes to the literature that discusses HFT behavior at the time of information releases or large price movements and that studies the impact of that behavior on market quality. For instance, Chordia et al. (2018) find that HFTs provide liquidity at the times of macroeconomic news announcements, while Brogaard et al. (2018) have a more nuanced result. They find that HFTs demand liquidity during "extreme price movements" that are correlated across stocks, i.e. upon the arrival of systematic or macro news, but that HFTs provide liquidity during firm-specific extreme price movements. Our study adds to that literature by showing that HFTs are able to profit from announcements that are expected but released at a random time, and how the resulting higher risk of adverse selection for slower traders can then negatively impact market quality for a substantial period of time ahead of the release of that information.

Finally, we note that our findings are clearly relevant beyond the case of central banks and the foreign exchange market, although that case provides an excellent environment to test the theories we discuss. Central bank monetary policy decisions are of critical economic importance for exchange rate determination, and the interdealer foreign exchange market, very large, very liquid and populated by a variety of trader types, reacts within milliseconds to that information. But the issues we address also apply to a number of other environments where information is expected but the exact timing of the information arrival is unknown ahead of time, for instance the impact on the equity, bond, or futures markets of some corporate earnings releases, judicial decisions or election results.

The paper proceeds as follows. In Section 2, we discuss the theoretical predictions. Section 3 introduces the data used in this study. In Section 4, we empirically test the theoretical predictions, documenting the impact that the two different central bank communication styles have on market liquidity and volatility. In Section 5 we analyze the pattern of trading profits among fast and and slow traders before and after central bank announcements, again showing the impact of the difference between the two communication styles. We conclude in Section 6.

2 Theoretical Predictions

In this section we discuss the predictions of theoretical models when market makers are concerned about either adverse selection costs (e.g., Kim and Verrecchia, 1994; Foucault et al., 2016; Dugast, 2018) or inventory management costs (e.g. Tinic, 1972; Amihud and Mendelson, 1980; Ho and Stoll, 1983; O'Hara and Oldfield, 1986). These models predict that illiquidity in the market should increase just before *pre-scheduled fixed-time* public announcements (announcements with a release date and time known in advance) because liquidity providers widen bid-ask spreads to be compensated for the possibility of adverse selection costs or inventory management costs. Consistent with these predictions, empirical studies (e.g., Kim and Verrecchia, 1994; Fleming and Remolona, 1997; Fleming and Piazzesi, 2005; Green, 2004) show an increase in illiquidity in the minutes before pre-scheduled public announcements for a broad range of assets, such as equities and sovereign bonds, and a broad range of announcements, including macroeconomic data and earnings announcements. These models also predict that market liquidity should not change prior to *unscheduled* public announcements (announcements that occur at an unknown date and time) because, by definition, liquidity providers cannot forecast release times and therefore assign a constant probability to the release of information at any point in time (see, e.g., Dugast, 2018).

To the best of our knowledge, the hybrid case of *pre-scheduled random-time* announcements (announcement that occur on a pre-announced date but at a random time) has not been considered in the theoretical literature before. Therefore we show next how that type of announcement can be introduced in a classic model where market makers face adverse selection costs. We then briefly discuss the impact of such announcements in the context of models where market makers face inventory management costs.

2.1 Glosten and Milgrom (1985) with a public announcement

To develop theoretical predictions regarding the behavior of liquidity prior to pre-scheduled random-time announcements, we introduce such an announcement into the Glosten and Milgrom (1985)'s model and solve the model for the resulting bid-ask spread.[4]

There is a single security traded at $t = 1, ..., n$, and its fundamental value at time t is given by the following equation:

$$v_t = v_{t-1} + \frac{1}{2}\sigma\delta_t, \quad t = 1, ..., n, \tag{1}$$

where $\delta_t = \pm 1$ with equal probability and δ_t is *iid* and independent from all other random variables in the model. Thus, the fundamental value at time t can take one of two values. A high value $(v_{t-1} + \frac{1}{2}\sigma)$ or a low value $(v_{t-1} - \frac{1}{2}\sigma)$ with equal probability (1/2).

Suppose that an announcement occurs on a known day but at a random time τ, $\tau \in \{1, ..., n\}$ (a case not considered by Glosten and Milgrom, 1985), and denote by p_t the probability assigned by the market maker at time $t-1$ to the event that $\tau = t$ given that $\tau \geq t$, i.e. that the announcement happens in the next period given that it has not occurred up to now. The announcement can either be good news or bad news with equal probability. During non-announcement periods, $t \neq \tau$, the fundamental value of the asset can take one of two values, a high value $(v_{t-1} + \frac{1}{2}\omega)$ or a low value $(v_{t-1} - \frac{1}{2}\omega)$ with equal probability (1/2). During the announcement period, $t = \tau$, the fundamental value can take one of two values. A high value $(v_{t-1} + \frac{1}{2}(\omega + \kappa))$ or a low value $(v_{t-1} - \frac{1}{2}(\omega + \kappa))$ with equal probability (1/2). In other words, we assume that the volatility of the fundamental value is given by the following equation:

$$\sigma = \begin{cases} \omega + \kappa & \text{if} \quad t = \tau, \\ \omega & \text{if} \quad t \neq \tau, \end{cases} \tag{2}$$

where κ measures the magnitude of the surprise contained in the announcement. If the announcement has not yet occurred, the market maker sets the spread knowing that the efficient price can take four different values in the next period: $v_{t-1} + \frac{1}{2}(\omega + \kappa)$ with probability $\frac{1}{2}p_t$; $v_{t-1} + \frac{1}{2}\omega$ with probability $\frac{1}{2}(1 - p_t)$; $v_{t-1} - \frac{1}{2}\omega$ with probability $\frac{1}{2}(1 - p_t)$; and $v_{t-1} - \frac{1}{2}(\omega + \kappa)$ with probability

[4] We adopt Foucault et al. (2013)'s description of Glosten and Milgrom (1985)'s model in Chapter 3, Section 3.3.

$\frac{1}{2}p_t$. Since the problem is similar to the one without a public announcement, the ask price takes the form $a_t = v_{t-1} + \frac{1}{2}s_t$ and we can find the optimal s_t rather than a_t.

We assume that at each period t the market maker sets bid and ask quotes observing the fundamental value in the previous period, v_{t-1}. The market maker knows that with probability π she will trade with an informed trader who observes v_t before she does and with probability $1-\pi$ she will trade with a liquidity trader who randomly buys or sells with equal probability regardless of v_t. Thus, conditional on $\tau \geq t$, the expected ask-side profit of the market maker at time $t-1$ when a trader buys the security at time t is given by

$$\mathbb{E}_{t-1}^{ask}(\Pi_t) = \begin{cases} \frac{1}{4}\pi[p_t(s_t - (\omega+\kappa)) + (1-p_t)(s_t-\omega)] + \frac{1}{4}(1-\pi)s_t & \text{if} \quad s_t \leq \omega, \\ \frac{1}{4}\pi_t p_t(s_t - (\omega+\kappa)) + \frac{1}{4}(1-\pi)s_t & \text{if} \quad s_t > \omega. \end{cases} \tag{3}$$

If the market maker sets the spread such that $s_t \leq \omega$, then the informed trader will always buy if a high value is realized ($\delta_t = 1$); with probability $\frac{1}{2}p_t$ the high value is $v_{t-1} + \frac{1}{2}(\omega+\kappa)$ and with probability $\frac{1}{2}(1-p_t)$ it is $v_{t-1} + \frac{1}{2}\omega$. If she sets the spread such that $s_t > \omega$, then the informed trader will only trade if $v_{t-1} + \frac{1}{2}(\omega+\kappa)$ is realized. The uninformed trader buys with the same probability regardless of the announcement. The expected profit function in (3) is increasing and piece-wise linear in s_t, and there is a unique s_t such that the expected profit is zero. If

$$p_t \leq \frac{(1-\pi)\sigma}{\pi\kappa} \tag{4}$$

the solution satisfies $s_t \leq \omega$ and it is given by

$$s_t = \pi(\omega + p_t\kappa). \tag{5}$$

If (4) does not hold, the solution satisfies $s_t > \omega$ and it is given by

$$s_t = \frac{\pi p_t(\omega+\kappa)}{1-\pi(1-p_t)}. \tag{6}$$

The value of the bid-ask spread over time conditional on $\tau \geq t$ depends on the conditional probability p_t, which is determined by the distribution of τ. For example, if τ is uniformly distributed on

$\{1, ..., n\}$,

$$p_t = \mathbb{P}(\tau = t | \tau >= t) = \frac{1}{n - t + 1}. \tag{7}$$

In this case, p_t monotonically increases with t. In general, p_t does not have to be monotonic in t, but it does eventually have to reach 1. Figure 2 illustrates the bid-ask spread as a function of the announcement's release times when we assume τ to be uniformly distributed (panel A and B) and when we use the empirical distribution of the BoJ release time in our sample (panel C and D). After the announcement occurs, the bid-ask spread returns to the usual value, because for the rest of the period the fundamental value can only change by $\pm\frac{1}{2}\omega$. Thus, conditional on $\tau < t$, $s_t = \pi\omega$ as in Glosten and Milgrom (1985)'s model.

Now for pre-scheduled fixed-time announcements (with τ fixed and known in advance, $p_t = 1$ for $t = \tau$ and zero otherwise), the bid-ask spread is constant up until the period immediately before the announcement, when it increases for one period and then returns to the pre-announcement level:

$$s_t = \pi(\omega + \kappa) \quad \text{if} \quad t = \tau, \tag{8}$$

$$s_t = \pi\omega \quad \text{if} \quad t \neq \tau. \tag{9}$$

For unscheduled public announcements (announcements with unknown date and time), market participants estimate the probability of the release of public information to be constant, $p_t = p$, and therefore the bid-ask spread is also constant:

$$s_t = \begin{cases} \pi(\omega + p\kappa), \text{ if } p \leq \frac{(1-\pi)\sigma}{\pi\kappa}, \\ \frac{\pi p(\omega+\kappa)}{1-\pi(1-p)}, \text{ if } p > \frac{(1-\pi)\sigma}{\pi\kappa}. \end{cases} \tag{10}$$

Since liquidity providers assign a constant probability to the release of announcements, this model predicts that illiquidity will not increase prior to the unscheduled public announcements, consistent with the predictions of Dugast (2018)'s model.

In summary, this simple model provides several hypothesis about the behavior of bid-ask spreads prior to pre-scheduled announcements that we will test empirically.

First, bid-ask spreads should increase only shortly before announcements with known date and release times (for ECB and Fed announcements). In contrast, as long as $\pi > 0$ and $\kappa > 0$, spreads should begin to increase well before announcements with known release dates but random release times (for BoJ announcements). In addition, for announcements with random release times, announcements that occur late in the range of possible release times will be associated with a higher bid-ask spread in the period immediately preceding each announcement than announcements that occur early in the range of possible release times, even if the expected magnitude of the surprise component of the announcement is similar in both cases.

Second, bid-ask spreads will be a function of p_t, which is related to the release time, and of the size of the surprise, κ. In our empirical work, we will test whether illiquidity prior to BoJ announcements is a function of the release time and of the expected size of the announcement surprise, and whether observed differences in illiquidity across central banks are fully explained once we account for the release time and the expected size of the surprise. To be clear, while surprises are, by definition, not expected, we believe that market participants form expectations about the size of the surprise of upcoming central bank announcement. We will use implied volatilities of exchange rates on the days immediately preceding each announcement day to measure these expectations.

Third, a higher probability of informed trading, π, should increase illiquidity. In our empirical analysis, arguing that fast traders have a form of information advantage, we will test whether the BoJ's unknown release time benefits fast traders and increases adverse selection costs for slow traders, therefore potentially causing higher illiquidity ahead of the release.

It is worth noting that both the prior literature and our empirical results show that bid-ask spreads stay elevated after the announcement is released, as it takes time for the new information released by the announcement to be fully incorporated into prices. This pattern holds for both fixed- and random-time announcements, unlike the pattern of the bid-ask spreads before announcements that we discuss above. The model we describe is not designed to capture the behavior of bid-ask spreads after announcements, nor do we study this pattern in more detail empirically, as this has been studied by others (e.g., Kim and Verrecchia, 1994). The focus of our paper is on what happens in the market in the period before central bank announcements.

2.2 Inventory Management Models without Asymmetric Information

Fleming and Remolona (1999) show that illiquidity in the U.S. Treasury market begins to increase about 10-minutes before pre-scheduled macroeconomic news announcements and stays elevated for about two-hours after the release. They discuss how the increase in illiquidity is consistent with inventory management models (e.g., Tinic, 1972; Amihud and Mendelson, 1980; Ho and Stoll, 1983; O'Hara and Oldfield, 1986), which emphasize the increased risk to market makers of high price volatility and one-sided order flow. In these models, even in the absence of informed traders, market makers demand compensation for bearing inventory management risk and set bid-ask spreads that are proportional to their expectation of future asset price volatility. In the case of a pre-scheduled announcement released at a random time, the bid-ask spread would be proportional to expected asset price volatility, $s_t \propto (p_t(\omega + \kappa) + (1 - p_t)(\omega))$, where p_t is the probability assigned by the market maker at time t-1 to the event that $\tau = t$ given that $\tau \geq t$. Thus, in inventory management models, illiquidity would also be expected to increase and stay elevated for a period of time prior to the random-time BoJ announcements, even without the effect of adverse selection costs.

Despite this shared prediction, there are obviously some important differences between other aspects of inventory management models and those of adverse selection models, such as Glosten and Milgrom (1985). In particular, bid-ask spreads in inventory management models are, by definition, not a function of the probability of trading with an informed trader, and effective spreads should not vary across investor types. Using trade-by-trade data, we study these issues in our empirical analysis, and we find evidence in support of the important role of adverse selection costs in explaining what we observe. In addition, we note again that Foucault et al. (2016) argue that, in a market with both fast and slow traders, there is inevitably some asymmetric information due the speed advantage of fast traders. Therefore, models that consider adverse selection costs faced by liquidity providers, such as Glosten and Milgrom (1985), clearly appear more relevant to the case we are studying than inventory cost models.

3 Data

3.1 Central Bank Announcements, Surprises and Volatility

In this study we compare the communication styles of three central banks, the Fed, the ECB and the BoJ. As we mentioned, the main difference between central bank communication practices that we focus on in our analysis is that, at the conclusion of their monetary policy meetings, the ECB and Fed release their monetary policy decisions at pre-scheduled fixed times, while the BoJ releases its decision at a random release time which comes a few minutes after the (unscheduled) end of its meeting. Figure 1 shows a distribution of the BoJ release times. During our sample period, October 2012 to December 2017, the BoJ released its monetary policy statement within a window of approximately three hours, ranging from 11:40 a.m. JST to 2:46 p.m. JST.

In Section 2 we showed that, irrespective of whether the precise release time of an announcement is known ahead of time or not, theory predicts that bid-ask spreads in the foreign exchange market should also be affected by the expected magnitude of the monetary policy surprise contained in that announcement, the κ in our theoretical discussion. In our empirical work, we will control for this determinant of liquidity using the euro-dollar and dollar-yen 1-month option-implied volatility one day before each central bank announcement; the daily data are obtained from Bloomberg. Also, to assess the actual amount of new information released by the central bank announcements, we will rely on ex-post monetary policy surprises derived from long-term government bond futures data following Rogers et al. (2014) and Rogers et al. (2018). Specifically, we focus on 10-year government bond yield changes from 15-minutes before the release of a monetary policy statement to 15-minutes afterwards.[5] We use the 10-year Japanese government bond futures for the BoJ announcements, 10-year Treasury futures for the Fed announcements, and both 10-year German Bund and 10-year Italian government futures for the ECB announcements to derive these estimates of monetary policy surprises; the intradaily futures data are obtained from Thomson Reuters.

We show summary statistics for these variables in Table 1. Focusing on the standard deviation of the surprises, we observe that the releases of Fed's monetary policy statements are associated with the largest government bond yield movements, suggesting that this announcement typically contains the most information, followed by the releases of ECB and BoJ monetary policy statements.[6] Turning to implied volatilities, the average one-month implied volatility across the days just before central bank announcements is a bit above 8% for euro-dollar and between 9 and 10% for dollar-yen, with little difference between the central banks. But there is considerable variation across announcements, as shown by the minima and maxima. Finally, the table also shows summary

[5]The changes in long-term interest rates are particularly relevant for measuring monetary policy surprises in a period when the central banks were engaging in quantitative easing and forward guidance, even when there was little variation in the main (short-term) policy rates.

[6]We also examine summary statistics of exchange rate movements around policy announcements, and look at the relationship between exchange rates and yield changes around policy announcements. Our conclusions are qualitatively similar.

statistics for the BoJ release times, which are defined as the number of hours between 11:30 a.m. JST and the time of each announcement (i.e. the minutes since 11:30 divided by 60). The variable takes a minimum value of 0.18 hours and a maximum value of 3.27 hours.

In Table 2, for each central bank and for the relevant exchange rates, we report the correlations between implied exchange rate volatilities on the days before announcements and the absolute value of the monetary policy surprises, adding also the BoJ release time to the correlations calculated for the BoJ. The correlations between implied volatilities and the absolute values of the surprises are all positive but not high, ranging from 0.01 to 0.41. We interpret these modest positive correlations as market participants having some ability, albeit quite imperfect, to predict whether central banks will surprise the public the next day. The correlation between dollar-yen implied volatility and the BoJ release time is essentially zero, which is helpful for our empirical analysis because it suggests that market participants do not anticipate the BoJ's release times. Finally, the correlation between the absolute value of the BoJ monetary policy surprise and the BoJ release time is 0.21. This positive correlation is consistent with the argument sometimes seen in the financial press that the longer the BoJ takes to release its decision, the larger the monetary policy surprise tends to be, but the correlation is weak.

3.2 The EBS interdealer market

Spot trading in major currency pairs (exchange rates) is conducted through a wide variety of venues, but two interdealer trading platforms, both central limit order books (CLOBs), are at the core of price discovery for the global foreign exchange market: EBS Market and Thomson Reuters Matching.[7] On these two platforms, the euro-dollar and dollar-yen currency pairs, the subjects of our study (and the currency pairs with the highest trading volume in the foreign exchange market), trade primarily on EBS, and the price-discovery process for these currency pairs is therefore concentrated on that platform. The EBS system is an interdealer system accessible to foreign exchange dealing banks and also, under the auspices of dealing banks (via prime brokerage arrangements), to non-banks, mostly high-frequency trading firms as well as some hedge funds and commodity trading

[7] Together, these two platforms are often known as the "primary market" for spot FX. The primary market was clearly central to price discovery in FX during our sample period. It remains quite important, but its role has been challenged by other trading venues in the last few years. The Thomson Reuters Matching platform has more recently been part of Refinitiv, which was then acquired by the London Stock Exchange Group (LSEG).

advisers (CTAs). The minimum trade size on EBS Market is 1 million of the “base” currency (i.e., the euro for euro-dollar and the dollar for dollar-yen), and trade sizes are only allowed in multiple of millions of the base currency.

3.3 Foreign Exchange Data

To analyze the behavior of various types of traders in the foreign exchange market, we use high-frequency EBS data for two currency pairs, euro-dollar and dollar-yen, from October 2012 to December 2017. Our sample begins in October 2012 because the tick size (minimum price fluctuation) on EBS decreased in March 2011 and then rose again in September 2012. The tick size changes affected bid-ask spreads, effective spreads, and trader participation in the EBS market as documented by Chaboud et al. (2024), and it could potentially contaminate our analysis of market quality.

Specifically, we use detailed data on both quotes and transactions. The quote data provides the first 10 levels of bid quotes and the first 10 levels of ask quotes, as well as the depth available at each of these 20 levels. All quotes are executable, therefore the top of the book quotes represent the true prices at which market participants could trade at that instant. The quote data are sampled every 100 milliseconds, providing a snapshot of the limit order book at that frequency.

The transactions data, recorded with millisecond precision, provide detailed information on both the volume and the direction of each trade. The direction of trade is based on actual trading records. A trade is recorded as buyer-initiated (seller-initiated) if it is the result of a “hit” on a posted ask (bid) quote. Importantly, we observe the type of maker and the type of taker for each trade using three different categories, Manual, Bank-AI, and PTC-AI, which are described below.

On the EBS trading platform, traders can enter trading instructions manually, using an EBS keyboard, or, upon approval, via a computer directly interfacing with the system. EBS records whether a trade was placed by a keyboard interface, or by a direct computer interface, allowing for a classification of trades into “human” or “computer” trades. This classification into manual (human) and algorithmic (computer) trading formed the basis for the study by Chaboud et al. (2014). The data used for the current paper allow for a finer classification of market participants, similar to the studies by Chaboud et al. (2024) and Chaboud et al. (2021).

In particular, the EBS data used in this paper break down the algorithmic market participants into two different categories, referred by EBS as Bank-AI and PTC-AI (AI stands for Automated

Interface, and PTC stands for Professional Trading Community). What allows for the distinction between the two groups of market participants that use a computer interface to access the EBS system is that the PTC-AI participants must access the system under a prime-brokererage agreement with a dealing bank, while the Bank-AI participants are dealing banks trading algorithmically on their own account. Since all non-banks are required to be prime-brokered onto the EBS system, and the vast majority of the PTC trading volume (over 90 percent) comes from HFT firms, this allows us to break down the EBS market participants into three types: The manual traders (M), the Bank-AI (B), and the PTC-AI (H), with the letter H chosen to represent HFT firms.

4 Empirical Analysis: Market Liquidity and Volatility

4.1 Identification of the Effect of the Unknown Release Time

A common way to identify the effect that a particular policy has on liquidity and volatility in a financial market would be to use a difference-in-difference methodology. The first difference would compare liquidity and volatility before and after the change in policy. The second difference would then compare the first difference of the treatment group (the one experiencing the change in policy) to the first difference of the control group (the one without a change in policy). In our analysis, the control group is the Fed and the treatment group is the BoJ. The change in policy is the move from announcing monetary policy decisions using a fixed pre-announced time to using a random time. However, the Bank of Japan switched to using a random release time in 2001, a period for which detailed EBS FX trading data are not available, and we cannot therefore use a standard difference-in-difference methodology.

Instead, we evaluate the impact that the random release time has on liquidity and volatility in the foreign exchange market by combining some aspects of a difference-in-difference methodology with an event-study methodology which compares the market behavior on announcement days to the market behavior on non-announcement days, as follows. For each BoJ and Fed announcement, we compare liquidity and volatility on non-announcement days (measured over the 10 business days preceding each announcement) to liquidity and volatility on announcement days. This gives us the first differences for our treatment and control central banks. We then compare the BoJ's first differences to the Fed's first-differences and derive our conclusions. In addition, using the exact same methodology, we also run a placebo test which compares the Fed to the ECB, two central banks that use a fixed pre-announced release time, expecting to find a very different result if the random release time has a substantial impact.

Of course, the fixed versus random release time is not the only thing that differs across central bank announcements. Crucially, while market participants can not predict the content of each central bank's announcement, they do form expectations about the likely amount of new information that will be released by each central bank and will impact exchange rates. The expected magnitude of that surprise will vary across central banks and across announcements. As described in Section 3 we control for this difference across central bank announcements and across time in the regression specification by using an indirect measure of the expected size of the surprise, the option-implied 1-month exchange rate volatility on the day before each announcement.

4.2 Effect of the Random Release Time on Market Liquidity

Before conducting a formal analysis, we first illustrate the effect of the random release time on market liquidity graphically. In Figure 3, we show average bid-ask spreads each minute for the relevant exchange rates on Fed, ECB and BoJ announcement days (the red lines) and on non-announcement days (the blue lines). The vertical line in each chart marks the release of the monetary policy statement. The differences between the BoJ and both the Fed and ECB announcements are striking. For the BoJ announcements, we find that the bid-ask spread starts increasing well in advance of the announcements and gradually rises until the actual releases, consistent with our theoretical model in Section 2. Upon the announcement, the bid-ask spread experiences a further upward jump before gradually declining to non-announcement-day levels. In contrast, for the Fed and ECB announcements, bid-ask spreads start widening only a few minutes prior to their announcements and peak right before the (known) time of the announcements. For the ECB, illiquidity (measured as bid-ask spreads) spikes twice, once when the ECB releases its statement and then 45-minutes later, at the time of its press-conference.[8] Similar to the BoJ, for the Fed and the ECB, bid-ask spreads then gradually return to normal levels.

[8]During our sample period, the Fed held a press conference after every other meeting (press conferences after each Fed meeting began in December 2018). The ECB's press conference, held after every meeting, was also widely viewed as more informative than the ECB's statement, while the Fed conveyed more information in its statement than the ECB. The BoJ held a press conference after each meeting in the late afternoon, usually several hours after the release of its statement.

The differences in the pattern of illiquidity across the three central banks is further highlighted in Figure 4, where we superimpose the Fed and the BoJ on one chart, showing dollar-yen bid-ask spreads, and the Fed and the ECB on the other chart, showing euro-dollar bid-ask spreads. While the period of illiquidity before monetary policy announcements is obviously longest for the BoJ, we also note that illiquidity is higher and longer-lasting after Fed announcements, likely because the information content of Fed announcements is higher on average, as was shown in Table 1, requiring a longer period of time for market participants to digest the news and fully incorporate it into prices.

Next we formally test for liquidity differences across announcement and non-announcement days and across central banks using a regression framework. Specifically, we compare BoJ and Fed liquidity in the USD/JPY currency pair using the following specification:

$$\begin{aligned}\ln(\text{Bid-Ask Spread}_{USDJPY,t}) = {} & \beta_A^{BoJ} Ann_t^{BoJ} + \beta_{NA}^{BoJ} NAnn_t^{BoJ} + \beta_A^{Fed} Ann_t^{Fed} \\ & + \beta_{NA}^{Fed} NAnn_t^{Fed} + \beta_{IV} \ln(\text{Implied Volatility}_{t-1}^{USDJPY}) \\ & + \beta_{RT}^{BoJ} \ln(1 + \text{BoJ Release Time}_t) + \varepsilon_{USDJPY,t}^{Spread},\end{aligned} \tag{11}$$

where $\ln(\text{Bid-Ask Spread}_{USDJPY,t})$ is the natural log of the average bid-ask spread in the dollar-yen exchange rate measured over three different time periods (the hour preceding each announcement excluding the very last minute, the minute immediately before each announcement and the minute immediately after each announcement); Ann_t^{BoJ} is an indicator variable equal to one on BoJ announcement days; $NAnn_t^{BoJ}$ is an indicator variable equal to one on BoJ non-announcement days, which we define as the 10 business days preceding each announcement day, with liquidity on those days measured over the exact same three time periods as for each subsequent BoJ announcement; Ann_t^{Fed} is an indicator variable equal to one on Fed announcement days; $NAnn_t^{Fed}$ is an indicator variable equal to one on Fed non-announcement days, which we define as the 10 business days preceding each Fed announcement, with liquidity on those days measured over the same time periods as for Fed announcement days[9]; $\ln(\text{Implied Volatility}_{t-1}^{USDJPY})$ is the natural log of dollar-yen implied volatility the day before; and $\ln(1 + \text{BoJ Release Time}_t)$ is the natural log of the number of hours from 11:30 am JST to the time of the announcement (minutes from 11:30 am JST to the time of the

[9]The Fed's fixed release time changes over our sample period. It is 2:15 pm ET at the beginning of our sample. Starting on March 20, 2013 all Fed monetary policy announcements then have a fixed release time of 2:00 pm ET, very precisely measured using US Naval Observatory time.

announcement divided by 60). The variable BoJ release time is equal to zero on non-announcement days, so we therefore add a one to the variable before taking the natural log. The regression is better specified using the natural log of bid-ask spreads rather than bid-ask spreads, as the dependent variable can then take both positive and negative values, the regression becomes less sensitive to outliers, and the residual of the regression is more likely to follow a normal distribution.

4.2.1 Liquidity in the Hour Before Announcements

Table 3 shows the results for the three periods over which we measure liquidity (t-60 to t-1, t-1 to t, and t to t+1, expressing time in minutes). Column 1 shows that bid-ask spreads during the hour (literally 59 minutes, but we will call it an hour for simplicity) before BoJ announcements are on average 1.40 pips ($1.40 = e^{0.34}$, where 0.34 is the coefficient estimate in the table), whereas on non-announcement days over the same time period bid-ask spreads are close to 1 pip ($1.1 = e^{0.1}$).[10] The difference between announcement and non-announcement days is statistically significant at the 1 percent level, and importantly the difference-in-difference between BoJ and Fed announcements (with $D_1 > D_2$) is also statistically significant at the 1 percent level. Therefore the statistical evidence supports the view that the manner in which the BoJ releases its monetary policy statement results in a substantial impairment of liquidity in the hour before the release, a phenomenon not observed for the Fed, consistent with the graphical evidence in figures 3 and 4.

In column 2 of Table 3, we control for the one-month dollar-yen implied volatility the day before announcements. We find that implied volatility has nontrivial explanatory power for the level of illiquidity during the hour prior to announcements. The associated coefficient is highly statistically significant and the adjusted R^2 increases when including implied volatility in the regression. However, implied volatility does not explain the difference in illiquidity in the hour before BoJ announcements relative to non-announcement days: the difference in the average log bid-ask spread ($D1$) is almost identical to the one derived from the regression without implied volatility, and it remains highly statistically significant. Likewise, adding implied volatility barely changes the corresponding difference for the Fed ($D2$), which remains statistically insignificant. As a result, the

[10] A pip is a measure widely used in the foreign exchange market to measure spreads and profits. For the dollar yen exchange rate, it is the second decimal quoted. For the euro-dollar exchange rate, it is the fourth decimal quoted. Therefore a pip is exactly equal to a basis point when the dollar-yen exchange rate is 100 yen per dollar or when the euro-dollar exchange rate is equal to 1. Given the ranges in which these two exchange rates fluctuated during our sample period, a pip and a basis point were broadly of the same magnitude during our sample period.

diff-in-diff ($D1 - D2$) also remains practically unchanged and highly statistically significant. These results suggest that differences in the expected information content of the Fed and BoJ announcements do not explain the elevated illiquidity prior to the BoJ announcements.

In column 3 we add the BoJ release time to the simple specification shown in column 1. We find that the BoJ release time is statistically significant and, importantly, fully explains the increase in illiquidity in the hour before BoJ announcements relative to nonannouncement days. The difference between the two ($D1$) becomes statistically indistinguishable from zero, and the diff-in-diff ($D1-D2$) also turns statistically insignificant. These results are consistent with the theoretical model in section 2, which suggests that illiquidity should begin to increase well before an expected announcement with an unknown release time, and that the later the announcement occurs, the higher the average illiquidity in the hour preceding the announcement should be. Importantly, column 4 shows that this result holds even when controlling for implied volatility the day before announcements. In fact, the coefficient from the BoJ release time becomes even more precisely estimated when controlling for implied volatility. These results suggest that differences in the timing of announcements explains the elevated illiquidity prior to BoJ announcements, consistent with the theoretical model in section 2.

4.2.2 Liquidity in the Minutes Before and After Announcements

Turning to the minute right before the announcements, we see in column 5 that illiquidity is higher for the Fed than for the BoJ (as indicated by the difference-in-difference $D_1 < D_2$). This is likely because, for the Fed, traders know with certainty during that minute that an announcement is about to be released, and also because the Fed tends to have larger monetary policy surprises than the BoJ, as indicated in Table 1. Thus in the minute before the Fed monetary policy statement is released, anticipated adverse selection and inventory management costs should clearly be higher for the Fed than for the BoJ. Column 6 confirms that the expected size of the monetary policy surprises, as measured by dollar-yen implied volatility the day before, is positively associated with illiquidity right before announcements.

As shown in columns 7 and 8, however, controlling for implied volatility the day before and, for the BoJ, for the actual BoJ release time, does not fully explain the level of illiquidity in the minute before Fed and BoJ announcements. The finding for the Fed is not too surprising, as implied dollar-yen volatility the day before is unlikely to be a perfect measure of the expected magnitude of the information content of the imminent Fed announcement. The low explanatory power of the BoJ release time for illiquidity during the minute before BoJ announcements is perhaps a bit more surprising given the results for the longer period before. We do not know precisely, however, how market participants form their expectations of the probability of an imminent release, and whether it is truly linear relative to the BoJ release time variable that we construct. For instance, it is possible, and even likely, that on BoJ announcement days, after a certain amount of time has passed without an announcement, some liquidity providers just exit the market until after the release has occurred, essentially behaving as if the probability of a data release in the next minute had converged to one. This possible scenario would obviously result in illiquidity not explained by our BoJ release time variable.

While our focus is primarily on what we observe in the market ahead of central bank announcements, the last 4 columns of Table 3, columns 9 through 12, report results for the minute immediately following each announcement. We note briefly that the results confirm that illiquidity is substantially higher immediately after Fed announcements than immediately after BoJ announcements ($Ann^{Fed} > Ann^{BoJ}$ and $D_1 - D_2 < 0$). This is consistent with the average size of the Fed surprises being larger than for BoJ surprises, as mentioned previously.

4.2.3 Placebo Test

To support the finding that the impact of the random timing of the release of BoJ's monetary policy statements on market liquidity is truly different from those of known-time announcements, we conduct a placebo test and an additional robustness check. First, we compare liquidity in the EUR/USD currency pair before and after ECB and Fed announcements. Second, we look at illiquidity prior to Japanese macroeconomic announcements with fixed pre-announced release times.

In our placebo test, we compare liquidity in the EUR/USD currency pair before and after ECB and Fed announcements using a similar specification to what we just employed to compare the BoJ and the Fed. Since both the Fed and the ECB release their monetary policy decisions at fixed, pre-announced times, we do not expect to find a statistically significant difference in illiquidity in the hour before the announcements are released. For the placebo test, we estimate the following equation:

$$\ln(\text{Bid-Ask Spread}_{EURUSD,t}) = \beta_A^{ECB} Ann_t^{ECB} + \beta_{NA}^{ECB} NAnn_t^{ECB} + \beta_A^{Fed} Ann_t^{Fed} + \beta_{NA}^{Fed} NAnn_t^{Fed} + \beta_{IV} \ln(\text{Implied Volatility}_{t-1}^{EURUSD}) + \varepsilon_{EURUSD,t}^{Spread}, \quad (12)$$

where $\ln(\text{Bid-Ask Spread}_{EURUSD,t})$ is the natural log of the average bid-ask spread in the euro-dollar exchange rate measured over our three different time periods (t-60 to t-1, t-1 to t, t to t+1); Ann_t^{ECB} is an indicator variable equal to one on ECB announcement days; $NAnn_t^{ECB}$ is an indicator variable equal to one on ECB non-announcement days, defined as the 10 business day preceding each announcement day, and with liquidity measured over the three same fixed time periods as for ECB announcement days; Ann_t^{Fed} is an indicator variable equal to one on Fed announcement days; $NAnn_t^{Fed}$ is an indicator variable equal to one on Fed non-announcement days, defined as for the ECB (with liquidity obviously measured over the three same time periods used for Fed announcement days); $\ln(\text{Implied Volatility}_{t-1}^{EURUSD})$ is the natural log of euro-dollar implied volatility the day before each announcement.

Table A1 in the Appendix shows the results for our three periods, with and without controlling for implied volatility. Columns 1 and 2 show that bid-ask spreads during the hour before ECB and Fed announcements are not statistically different from each other, as indicated by the very small and statistically insignificant differences-in-differences. This stands in contrast to what we observed when we compared the impact of the BoJ and the Fed announcements using a similar methodology, which highlighted the unusual impact of the BoJ's random release time. The differences in illiquidity between the Fed and the ECB become statistically significant when measured over the minute before and the minute after their announcements, with illiquidity higher for Fed announcements than that for ECB announcement ($D_1 < D_2$). This is again consistent with the Fed statements being more informative (and being expected to be more informative) than the ECB statements, as discussed previously.

4.2.4 Additional Robustness Check

Finally, to investigate the possibility that the behavior of dollar-yen bid-ask spreads before BoJ announcements is a general feature of Japanese news announcements rather than being driven by the randomness of the BoJ announcement time, we briefly examine bid-ask spreads around two important Japanese macroeconomic announcements during our sample period, GDP and TANKAN, both of which are released quarterly on pre-announced days at 8:50 am JST.[11]

Figure A1 in the Appendix shows, in panels A and B, average dollar-yen bid-ask spreads on EBS in a window around the fixed time of the GDP and TANKAN announcements (the red line), as well as in the same time window for non-announcement days (the blue line). There is a spike in bid-ask spreads in a narrow window around the release time on announcement days, as expected. Importantly, although the red line is clearly more jagged because of the small sample size of these announcements, the difference in bid-ask spreads between announcement and non-announcement days is small in the period before the announcements, in stark contrast to what we observed for the BoJ data releases, where bid-ask spreads were elevated for a substantial period of time before the announcements.[12]

4.3 Effect of the Random Release Time on Realized Volatility

There is a large literature that studies the relationship between volatility, liquidity, and public announcements (see, for example, Bollerslev et al., 2018; Nguyen et al., 2020). The literature generally focuses on the effect that information has on volatility and liquidity after announcements are released, and it broadly finds that the arrival of information is immediately followed by higher volatility, higher trading volume, and higher transaction costs. One theoretical explanation for this association is that agents disagree on the interpretation of the news (Harrison and Kreps, 1978; Harris and Raviv, 1993; Kandel and Pearson, 1995; Scheinkman and Xiong, 2003; Banerjee and Kremer, 2010), with the release of news then causing an increase in trading volume and volatility. Another explanation is that investors have different expectations prior to public announcements (Kyle, 1985; Kim and Verrecchia, 1991, 1994), which then causes an increase in trading volume and

[11] The Tankan is an influential business sentiment survey conducted and released by the Bank of Japan.

[12] We note that the steady decline in bid-ask spreads on both announcement and non-announcement days observed in the charts is associated with the gradual increase in foreign exchange trading activity at the beginning of the trading session in Tokyo. Recall that the two macro announcements occur at 8:50 am JST.

volatility as traders update their priors upon the release of new information. Within this context, the empirical literature has often focused on the relationship between trading volume and volatility, especially after the release of information. In contrast, our study focuses on the behavior of market liquidity (bid-ask spreads) and volatility prior to the release of new information, consistent with the theoretical predictions discussed in section 2. Having shown that illiquidity increases well ahead of the release of BoJ announcements but not ahead of Fed or ECB announcements, we now study the behavior of volatility over the same time periods.

We formally test for differences in volatility across announcement and non-announcement days and across the Fed and the BoJ using a regression specification similar to what we used for liquidity:

$$\begin{aligned}\ln(\text{Realized Volatility}_{USDJPY,t}) = {} & \beta_A^{BoJ} Ann_t^{BoJ} + \beta_{NA}^{BoJ} NAnn_t^{BoJ} + \beta_A^{Fed} Ann_t^{Fed} \\ & + \beta_{NA}^{Fed} NAnn_t^{Fed} + \beta_{IV} \ln(\text{Implied Volatility}_{t-1}^{USDJPY}) \\ & + \beta_{RT}^{BoJ} \ln(1 + \text{BoJ Release Time}_t) + \varepsilon_{USDJPY,t}^{RV},\end{aligned} \tag{13}$$

where $\ln(\text{Realized Volatility}_{USDJPY,t})$ is the natural log of realized volatility in the dollar-yen exchange rate measured over our three time periods (t-60 to t-1, t-1 to t, t to t+1, with time measured in minutes); Ann_t^{BoJ} is an indicator variable equal to one on BoJ announcement days; $NAnn_t^{BoJ}$ is an indicator variable equal to one on BoJ non-announcement days, defined as the 10 business days preceding each announcement day, and with volatility measured over the same three time periods used for the subsequent BoJ announcement; Ann_t^{Fed} is an indicator variable equal to one on Fed announcement days; $NAnn_t^{Fed}$ is an indicator variable equal to one on Fed non-announcement days, defined as the 10 business days preceding each announcement, and with volatility measured over the three same fixed time periods as used for Fed announcement days; $\ln(\text{Implied Volatility}_{t-1}^{USDJPY})$ is the natural log of dollar-yen implied volatility the day before; and $\ln(1 + \text{BoJ Release Time}_t)$ is the natural log of the number of hours from 11:30 a.m. JST to the time of the BoJ announcement (minutes between 11:30 a.m. JST and the time of the announcement divided by 60). To measure realized volatility in the one-hour (59 minutes) period, we sum squared one-minute returns over the interval. For the one-minute periods, we simply square the one-minute returns. For the same reasons as for our corresponding analysis of illiquidity, the regression above is better specified using the natural log of realized volatility rather than realized volatility itself.

The results in columns 1-4 of Table 4 show that volatility in the hour before BoJ announcements is higher than in the same period before Fed announcements ($D_1 > D_2$). This difference-in-difference remains statistically significant when we control for USD/JPY implied volatility the day before, but it does not remain statistically significant when we control for the BoJ release time. These results, together with the results shown in Table 3, are clearly consistent with the illiquidity observed well ahead of each announcement contributing to the higher volatility that we observe during the same period. During the one-minute intervals before and after announcements, Columns 5-12 show that volatility is higher for the Fed than for the BoJ, a difference that remains statistically significant even after controlling for implied volatility and BoJ release times. Again, this is consistent with the information content of Fed announcements often being higher than that of BoJ announcements.

Looking at the magnitude of the changes in liquidity and volatility, we find that in the hour before BoJ announcements, when illiquidity is present because of the upcoming announcement but no new information has yet been released, the bid-ask spread in the dollar-yen market increases on average by almost 30% as does realized volatility.[13] In the minute after announcements, however, when information has just been released, the bid-ask spread almost doubles on average, and volatility is almost five times higher.[14] So, while the pre-announcement effect on liquidity and realized volatiliy is notable, it is clearly smaller than the effect of the information release itself, as would be expected.

Similar to what we did for our analysis of liquidity, we also run a placebo test for volatility where, using the methodology just described, we compare the market's reaction to Fed and ECB announcements, the two central banks with a fixed release time. The results, presented in Table A2 in the Appendix, show no statistically significant difference in volatility between the Fed and the ECB in the hour before announcements, in contrast to what we observed when comparing the BoJ and the Fed. The difference becomes statistically significant only in the minutes before and after the announcements, with volatility higher for the Fed than for the ECB. This is consistent with the liquidity results and, again, with the fact that the information content of Fed monetary policy statements is typically higher than that of ECB statements. Finally, also similar to what we did

[13] More precisely, Table 3 Column 1 indicates that the increase in illiquidity one hour before is $\frac{e^{0.338}-e^{0.099}}{e^{0.099}} \times 100 = 27$ percent. Table 4 Column 1 indicates that the increase in volatility one hour before is $\frac{e^{0.263}-e^{0.018}}{e^{0.099}} \times 100 = 28$ percent.

[14] More precisely, Table 3 Column 9 indicates that the relationship between illiquidity one minute after on announcement days compared to nonannouncement days is $e^{0.674} \approx 2 \times e^{0.076}$. Table 4 Column 9 indicates that the relationship between volatility one hour after on announcement days compared to nonannouncement days is $e^{2.052} \approx 5 \times e^{0.465}$.

for liquidity, we plot in Figure A1, Panels C and D, the dollar-yen realized volatility around two pre-scheduled, fixed-time Japanese macroeconomic announcements, GDP and TANKAN. Relative to non-announcement days, we observe no discernible increase in realized volatility in advance of those announcements, ruling out the possibility that the observed increase in realized volatility ahead of the BoJ announcements is a general feature of Japanese economic data releases.

4.4 Effect of the Random Release Time on the Joint Dynamics of Market liquidity and Volatility

In the previous sections, we analyzed the effect that the random release time has on market liquidity and volatility in isolation. Previous literature, however, has often shown that volatility and liquidity interact dynamically, and in this section we therefore study the joint dynamics of intraday liquidity and volatility around central bank announcements. We allow for illiquidity to affect volatility and vice-versa, and we study how that relationship varies in three different periods, the hour before central bank announcements, the hour after announcements, and the same periods on non-announcement days. In particular, we are interested in understanding how the illiquidity induced by the random release time affects volatility and how persistent this effect is.

Following Nguyen et al. (2020), we use a multivariate logarithmic autoregressive conditional duration model, log-ACD(1,1), originally proposed in a univariate setting by Bauwens and Giot (2000). Nguyen et al. (2020) allow for contemporaneous effects and identify the model using assumptions regarding the order of causality based on theory. Using similar assumptions, we estimate the model allowing for contemporaneous effects as well. However, we also estimate the model without contemporaneous effects. The advantage of this specification is that we do not need to assume an order of causality, and the data then dictates which variable, volatility or illiquidity, has a larger effect on the other. Since the model without contemporaneous effects leads to very similar results as the model with contemporaneous effects, we report in the main text the results of the model without contemporaneous effects, and we report the results with contemporaneous effects in the Appendix.

Another difference between our specification and that of Nguyen et al. (2020), is that they estimate a three-variable system: liquidity (depth), volatility, and trading volume. Instead, we estimate a two variable system: illiquidity (bid-ask spreads) and realized volatility. In our study, a two-variable system is more appropriate than a three-variable system because, even in a market as active as the interdealer foreign exchange market, it is not unusual for trading volume to be zero for entire minutes during the hour preceding central bank announcements.[15] As a log-ACD(1,1) model cannot accommodate variables that take zeros values, one must then adopt numerical "tricks," such as replacing zero values on the right-hand side of the model by a very small positive number, to address the issue. As long as the zeros are not common, this does not affect the results in a notable way. In our case, however, as there is a non-trivial mass at zero for trading volume, as seen in figure A2, we find that the magnitude of the results has some sensitivity to the exact method used to replace the zeros, although the qualitative conclusion is preserved. Therefore, while we report the results of a three-variable system in the Appendix, we only show results for the two-variable system in the main text.

4.4.1 Specification of the Joint Dynamics of Illiquidity and Volatility

We first describe briefly how we model the joint dynamics of illiquidity and volatility.[16] We denote days with the index t, $t = 1, ...T$, where for each announcement we include the announcement day and the 10 preceding trading days (non-announcement days), i.e. $T = n_{ann}(1 + 10)$ where n_{ann} denotes the number of announcements. We denote minutes with the index i, and $i = -60, ..., -1, 1, ..., 60$ covering the 60 minutes before and 60 minutes after announcements. In the estimation, we exclude the minute immediately before the announcement to match the period we label pre-announcement period in sections 4.2 and 4.3. For each one-minute interval, we calculate the average top-of-the-book bid-ask spread, $s_{i,t}$, and the realized volatility, $\sigma_{i,t}$, using the 100-millisecond order book data within the minute.[17]

We model the vector $\boldsymbol{y}_{i,t} := (s_{i,t}, \sigma_{i,t})'$ using a log-ACD(1,1) specification. The version without contemporaneous effects is given by:

$$\boldsymbol{y}_{i,t} = \exp(\boldsymbol{\psi}_{i,t}) \odot \boldsymbol{\varepsilon}_{i,t}, \tag{14}$$

$$\boldsymbol{\psi}_{i,t} = \boldsymbol{\omega} + \boldsymbol{A}_1 \log(\boldsymbol{y}_{i-1,t}) + \boldsymbol{B}\boldsymbol{\psi}_{i-1,t}, \tag{15}$$

[15] In contrast, bid-ask spreads (our measure of illiquidity) are never equal to zero, and one-minute realized volatility is only infrequently equal to zero.

[16] For a more detailed description, please refer to Nguyen et al. (2020), Bauwens and Giot (2000), and Manganelli (2005), among others

[17] The results are qualitatively similar if we use the realized kernel of Barndorff-Nielsen et al. (2008), which is robust to market microstructure noise, to construct $\sigma_{i,t}$.

where $\boldsymbol{\psi}_{i,t} := (\psi^s_{i,t}, \psi^\sigma_{i,t})'$ is the log of the conditional mean of $\boldsymbol{y}_{i,t}$ and $\boldsymbol{\varepsilon}_{i,t} := (\epsilon^s_{i,t}, \epsilon^\sigma_{i,t})'$ is a multiplicative error term whose elements follow independent (across elements and over time) zero-augmented log-normal distributions with unit mean.

To study how the level and dynamics of $\boldsymbol{y}_{i,t}$ change around monetary policy announcements, we introduce a dummy variable $D^b_{i,t}$ that equals one for the hour before an announcement (excluding the minute before), a dummy variable $D^a_{i,t}$ that equals one for the 60 minutes after an announcement, $D^a_{i,t}$, and a dummy variable $D^n_{i,t}$ that equals one for non-announcement days for the 120 minutes corresponding to the same 60 minutes before and after the upcoming announcement.[18] We then estimate the following specification for $\boldsymbol{\psi}_{i,t}$ for the model without contemporaneous effects:

$$\boldsymbol{\psi}_{i,t} = (\boldsymbol{\omega}_n D^n_{i,t} + \boldsymbol{\omega}_b D^b_{i,t} + \boldsymbol{\omega}_a D^a_{i,t}) + (\boldsymbol{A}^n_1 D^n_{i,t} + \boldsymbol{A}^b_1 D^b_{i,t} + \boldsymbol{A}^a_1 D^a_{i,t}) \log(\boldsymbol{y}_{i-1,t}) + \boldsymbol{B}\boldsymbol{\psi}_{i-1,t}, \qquad (16)$$

We estimate the model by quasi maximum likelihood, replacing zero values in $\boldsymbol{y}_{i-1,t}$ on the right-hand side of $\boldsymbol{\psi}_{i,t}$ by the relevant sample minima divided by 100. We also include a dummy variable for the first observation on each sample day to capture any overnight effects.

Table 5 reports the estimated parameters of the volatility equation of the log-ACD(1,1) model in (16). In the left panel, we present estimates for the BoJ and Fed announcements in the USD/JPY market. In the right panel, we show the estimates for the ECB and Fed announcements in the EUR/USD market. Focusing on the BoJ-Fed panel, we first see that illiquidity has a clear impact on future volatility in all regimes and for both central banks. When there are no monetary policy announcements or during the hour that follows announcements, the difference between the BoJ and the Fed in the effect that lagged illiquidity has on volatility is small and not statistically significant. In contrast, during the hour before monetary policy announcements, lagged illiquity has a significantly larger effect on volatility for the BoJ than for the Fed, as shown by the estimated coefficients for $D^b_t \log(\sigma_{t-1})$. This suggests that the random release time not only increases the level of illiquidity during the hour before BoJ announcements, as we showed earlier, but that it also appears to increase the sensitivity of volatility to that illiquidity. The right panel strongly suggests that this result is unlikely to be driven by some peculiarity with the impact of illiquity on volatility associated with Fed announcements. In fact, when we compare the impact of illiquidity on future

[18] Results are identical if we allow for two separate dummies for the 60 minutes before and after the announcement.

volatility before ECB announcements and before Fed announcements in the EUR/USD market, we find that illiquidity has a larger impact on future volatility for Fed announcement than for ECB announcements. Next, to investigate how persistent the effect of illiquidity on volatility is around these central bank announcements, we conduct an impulse-response analysis.

4.4.2 Impulse Responses

The log-ACD(1,1) model is non-linear and the associated impulse response function therefore depends on the initial conditions and shock size. We follow Manganelli (2005), who derives an impulse response function for a standard ACD model, $\partial \mathbb{E}(\boldsymbol{\psi}_t|\Omega_0)/\partial \boldsymbol{\varepsilon}_0{}'$, $t \geq 0$, assuming that the system is initially at a steady state. Our case is more involved, however, given the additional nonlinearity of the log-ACD specification, as we need to derive $\partial \mathbb{E}(\exp(\boldsymbol{\psi}_t)|\Omega_0, \boldsymbol{\varepsilon}_1 = \cdots = \boldsymbol{\varepsilon}_t = \boldsymbol{\imath})/\partial \boldsymbol{\varepsilon}_0{}'$, $t \geq 0$. We describe the derivation in the Appendix.

Figure 5 shows the effect of illiquidity (the impulse) on realized volatility (the response) implied by the estimated log-ACD(1,1) models, separately for the hour before announcements, the hour after announcements, and on non-announcement days. The full impulse response functions are shown in the Appendix.[19] Figure 5 shows that illiquidity has a larger, more persistent impact on volatility before BoJ announcements than before Fed and ECB announcements. This result suggests that the unknown release time may exacerbate the potentially de-stabilizing feedback relationship between volatility and illiquidity, where the unknown release time causes illiquidity, which in turn causes more volatility, contributing to further illiquidity. We also note that, for the BoJ but not for the Fed, the feedback relationship between liquidity and volatility is significantly larger before announcements than after announcements, likely as the resolution of uncertainty post-BoJ announcements greatly reduces concerns among traders about asymmetric information and adverse selection. In terms of the economic magnitude of the effects, we find that the effect that illiquidity has on volatility is larger than the effect that volatility has on illiquidity (see figures A3 and A4 in the Appendix), consistent with the finding of Nguyen et al. (2020).

[19] Specifically, Figure A3 shows the four impulse response functions for the two-variable system estimated around BoJ announcements, and Figure A4 shows the four impulse response functions for the two-variable system estimated around Fed announcements.

4.4.3 Impulse Response Robustness Checks

As a first robustness check, we estimate a trivariate system of equations (illiquidity, volatility and trading volume). Specifically, we model the vector $\boldsymbol{y}_{i,t} := (s_{i,t}, \sigma_{i,t}, v_{i,t})'$, where $v_{i,t}$ is trading volume. The results are shown in the Appendix. Figure A5 shows that, as far as the relationship between illiquidity and volatility, the impulse response functions for the trivariate system estimated during BoJ announcements are broadly similar to the results derived in the bivariate system. Recall that the bivariate system avoided the issue created by the relatively frequent intervals of zero trading volume ahead of central bank announcements.

As a second robustness check, we estimate a bivariate system of equations for illiquidity and volatility that allows for contemporaneous effects. Specifically, we re-write equation 14 as follows:

$$\boldsymbol{y}_{i,t} = \exp(\boldsymbol{\psi}_{i,t}) \odot \boldsymbol{\varepsilon}_{i,t}, \tag{17}$$

$$\boldsymbol{\psi}_{i,t} = \boldsymbol{\omega} + \boldsymbol{A}_0 \log(\boldsymbol{\varepsilon}_{i,t}) + \boldsymbol{A}_1 \log(\boldsymbol{y}_{i-1,t}) + \boldsymbol{B}\boldsymbol{\psi}_{i-1,t}, \tag{18}$$

To identify $\boldsymbol{A}_0$, we assume the same ordering as Nguyen et al. (2020), namely that $\sigma_{i,t} \to s_{i,t}$, so that $\boldsymbol{A}_0$ is upper triangular with zeros on the diagonal, $\boldsymbol{\omega}$ and $\boldsymbol{A}_1$ are unrestricted and $\boldsymbol{B}$ is a diagonal matrix. The results are shown in Figure A6 the Appendix. The figure shows that the results are quite similar to results derived from a bivariate system without a contemporaneous relationship.

Overall, our empirical analysis of how market liquidity is affected by the random release time used by the Bank of Japan when it releases its monetary policy announcement clearly confirms the predictions of the modified Glosten and Milgrom (1985) model discussed in Section 2. Illiquidity begins to increase well ahead of the BoJ announcements, in contrast to what we observe for the Fed and ECB announcements. Realized volatility also increases before the BoJ announcements in spite of the absence of new information, with volatility showing heightened sensitivity to illiquidity as market participants await the upcoming release. As the literature has generally been silent about what may cause illiquidity and volatility in a financial market in the absence of new information, we note that this is a useful example of such a mechanism and potentially a novel contribution to the literature. We discuss next how the interaction of fast and slow traders in the foreign exchange market appears to contribute to the illiquidity observed before the BoJ announcements.

5 Empirical Analysis: Adverse Selection and The Trading Profits of Fast and Slow Traders

Having established that illiquidity in the hour before BoJ announcements is notably higher than illiquidity in the hour preceding Fed and ECB announcements, we now investigate whether this may be exacerbated by a higher risk of adverse selection of liquidity providers associated with the random time used by the BoJ to release its monetary policy statement.

Recall that fast and slow traders coexist on the EBS trading platform, specifically manual traders (slow), bank algo traders (faster) and HFTs (fastest). As is the case for other types of news, there is little doubt that fast traders can process and react to the information content of central bank announcements more quickly than slower traders, and the data show that they are quite active at those times. In fact, using a totally different source of data, Goshima and Kumano (2019) discuss in a BoJ paper how a notable number of unique IP addresses repeatedly connect to the BoJ monetary policy statement web page ahead of the release of the statement, which they interpret as evidence of heightened activity by HFT firms on the days of monetary policy announcements.

As discussed for instance by Haldane (2011), O'Hara (2016), and also in Foucault et al. (2016) when they introduce the concept of *news trading*, the difference in speed among traders creates short-lived periods of information advantage for the fastest traders immediately upon the release of information. That is very likely the case for the three central bank announcements that we study. But above and beyond that, we argue that the variability of the release time of the BoJ statement may create an additional layer of information advantage between fast and slow traders as, in contrast to the Fed and ECB releases, the slow traders do not know precisely when they will or will not be most at risk of adverse selection by fast traders. The higher risk of adverse selection by fast traders, in turn, may then further increase illiquidity and volatility in the market.

To investigate the extent of adverse selection immediately following BoJ and Fed announcements, we compute the profitability of liquidity demand ("taking") and liquidity supply ("making") by our three types of market participants (manual traders, bank algos and HFTs, or M, B, and H) in a one-minute period following monetary policy announcements. To be clear, we do not observe actual profits realized on each trade by individual market participants, as our data do not identify individual market participants. Instead we calculate potential profits for each trade based on subsequent price movements, which then allows us to study profitability by type of liquidity-demanding trader (D) and liquidity-supplying trader (S). We focus on the one-minute period following central bank announcements because this is when adverse selection costs are highest (Foucault et al., 2016), as the information advantage enjoyed by the fastest traders upon the release of new information dissipates very quickly.

We define potential liquidity demand profits for the i^{th} trade, which occurs at time t by the D taker type as:

$$\text{Liquidity Demand Profit}_{i,t}^{D} = q_i^D(m_{t+n} - p_i^D) \tag{19}$$

where q_i^D is an indicator variable for a trade with a D taker type (D={M, B, H}) that equals +1 when D is buying the base currency (i.e. a buyer initiated trade) and -1 when D is selling the base currency (i.e. a seller-initiated trade), p_i^D is the transaction price for that trade, and m_{t+n} is the quote midpoint prevailing n seconds after the trade occurs.[20] We follow Chaboud et al. (2024) and set $n = 5$ seconds.

Similarly, we compute liquidity supply profits using the realized spread formula for each liquidity supplier S:

$$\text{Liquidity Supply Profit}_{i,t}^{S} = q_i^S(m_{t+n} - p_i^S) \tag{20}$$

where q_i^S is an indicator variable for a trade with an S maker type (S={M, B, H}) that equals +1 when S is buying the base currency (i.e. a buyer initiated trade) and -1 when S is selling the base currency (i.e. a seller-initiated trade), p_i^S is the transaction price for that trade, and m_{t+n} is the quote midpoint prevailing 5 seconds after the trade occurs ($n = 5$).

We formally test for differences in trading profits by various types of traders across announcement and non-announcement days and across central banks using the following regression specification, here shown for liquidity demand:

$$\begin{aligned}\text{Liquidity Demand Profit}_{i,t}^{D} = \beta_A^{D,BoJ} Ann_t^{BoJ} + \beta_{NA}^{D,BoJ} NAnn_t^{BoJ} + \beta_A^{D,Fed} Ann_t^{Fed} \\ + \beta_{NA}^{D,Fed} NAnn_t^{Fed} + \varepsilon_{USDJPY,t}^{DP},\end{aligned} \tag{21}$$

[20]The base currency for the USD/JPY currency pairs is the dollar, and the base currency for the EUR/USD currency pair is the euro.

where Liquidity Demand $\text{Profit}_{i,t}^{D}$ are liquidity demand profits for the i^{th} trade during the one-minute period immediately following an announcement, as defined in equation 19; Ann_t^{BoJ} is an indicator variable equal to one on BoJ announcement days; $NAnn_t^{BoJ}$ is an indicator variable equal to one on BoJ non-announcement days, defined as the 10 business days preceding each announcement, with profits measured during the same one-minute period as for the subsequent announcement day; Ann_t^{Fed} is an indicator variable equal to one during Fed announcement days; $NAnn_t^{Fed}$ is an indicator variable equal to one on Fed non-announcement days, defined in a manner similar to the BoJ case.

Panel A of Table 6 shows the liquidity-demand profit results for the one-minute period immediately following the release of monetary policy statements by the BoJ and Fed. The table shows that the largest profits are earned by HFTs taking liquidity after the release of the BoJ MP statement. On average, these HFTs earn 1.187 pips per trade in the minute following the BoJ statement, compared to 0.051 pips they earn on average in the same minute of the trading day on non-announcement days. The difference, 1.136 pips, is statistically significant at the 1 percent level, as indicated by $D1$ in the table. In contrast, liquidity-taking HFTs earn a much smaller profit per trade in the minute following Fed announcements, a profit which is not significantly different from what similar trades earn on non-announcement days, as indicated by $D2$ in the table. Moreover, the difference -in-difference between the BoJ and the Fed ($D1 - D2$) is equal to 1.1 pips and is highly statistically significant, strongly suggesting that the way in which the BoJ releases its monetary policy announcements favors the most technologically-advanced traders when they trade aggressively. We note that liquidity taking by bank algos during those one-minute intervals is also unusually profitable, although not quite as much as for HFTs.

The size of the "excess profits" earned by liquidity-taking HFTs immediately after BoJ announcements is economically significant. At 1.1 pips, the diff-in-diff ($D1 - D2$) is approximately equal to the average bid-ask spread in the USD/JPY market during our sample period, implying that HFTs earn an excess profit on each liquidity-taking trade that is roughly equal to the profit a market maker would earn on the two transactions needed for a "round-trip" in normal times. In dollar terms, for a median trade size of \$1 million, with the mean only a bit larger, HFTs earn just under \$120 on average per liquidity-taking trade in the minute after each BoJ monetary policy announcement. Multiplying by 133, which is the average number of HFT-taker trades in our sample during the first minute after BoJ announcements, and then by 8, which is the number of regularly-scheduled BoJ meetings per year in the latter part of our sample, yields total dollar profits of about $127,000 per year for the HFT takers. While this is not a completely negligible amount given that it is earned during a mere 8 minutes of the whole trading year, it is not large for such a massive financial market. But what is most relevant here is that these liquidity-taking profits are, by definition, liquidity-making losses for the counterparties to these trades. In other words, contributing to the long period of illiquidity as traders face the possibility of a BoJ announcement, the minutes immediately following these announcement are particularly dangerous minutes to be a liquidity provider, especially for the slowest traders, as we show next.

Panel B of Table 6 shows average liquidity-supply profits for our three types of traders measured in the one-minute periods immediately following the BoJ and Fed monetary policy announcements, using the regression specification used in Equation 21. The table shows that, during the minute that immediately follows BoJ monetary policy releases, the three types of liquidity providers experience losses on average. But manual liquidity providers, our slowest traders, experience by far the largest losses. On average, manual liquidity providers lose 1.422 pips per trade in the minute after BoJ releases, a much larger loss than the 0.086 pips they typically lose in the same minute of the trading day on non-announcement days, with the difference being highly statistically significant. We note that, in contrast, the trades of manual liquidity providers in the minute following the fixed-time Fed announcements show gains at a five-second horizon, notably better than during the same minutes on the ten days preceding Fed announcement days. The difference-in-difference between the BoJ and the Fed ($D1 - D2$) shows a loss of 1.787 pips per trade, which is highly statistically significant.

Together, the evidence on liquidity-demand profits and liquidity-supply profits that we have just shown strongly suggests that the random release time used by the BoJ provides a substantial advantage to fast traders who, immediately after the BoJ announcements, consume the liquidity provided by slower traders. In turn, heightened concerns by potential liquidity providers about being adversely selected in a severe manner on BoJ announcement days then very likely exacerbates the magnitude of the illiquidity that we observe for a lengthy period of time ahead of BoJ announcements.

6 Conclusion

We show that the way in which the Bank of Japan releases its monetary policy decision to the public has a very different impact on the foreign exchange market than what we observe for the Federal Reserve and the European Central Bank. In particular, BoJ monetary policy announcements are often preceded by a long period of low liquidity and high volatility in the market, a period that can last up to several hours. In contrast, for the Fed and ECB, liquidity and volatility in the FX market begin to be affected by the upcoming release of their monetary policy decisions only a few minutes ahead of the announcements. As we show both theoretically and empirically, what causes this very different effect on market functioning is that, while the precise day and time of Fed and ECB monetary policy announcements are well known to the public, BoJ monetary policy decisions are released on a pre-announced day but at a time that is not pre-announced and can vary by several hours. Concerns about adverse selection when the announcement is finally released then causes liquidity providers to behave defensively as the market waits for the BoJ release, causing the extended period of illiquidity.

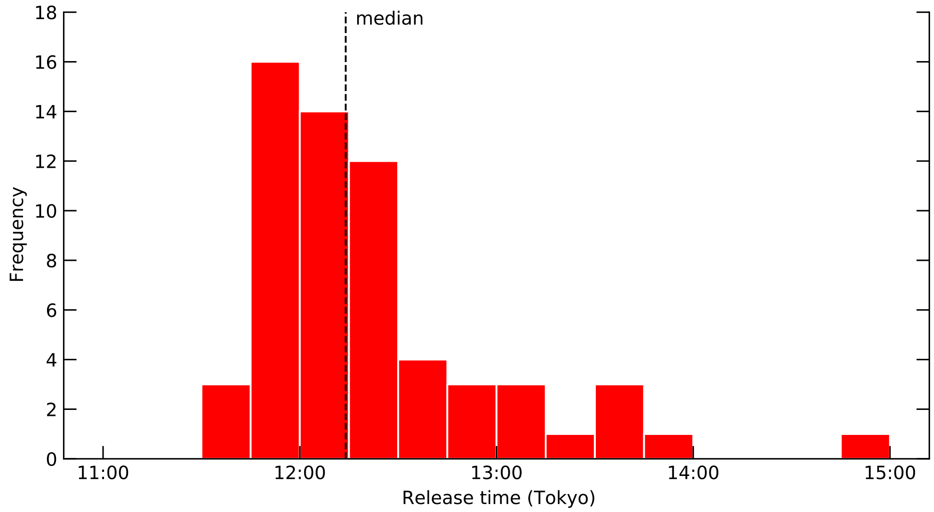
Our results also suggest that the interaction between fast and slow traders in the foreign exchange market very likely amplifies the illiquidity observed in the market well ahead of the BoJ announcements. In particular, using very precise FX trading data from EBS that allows us to observe the behavior of several types of market participants, we show that fast traders who consume liquidity derive substantially larger trading profits immediately after the random-timed BoJ announcements than immediately after the fixed-timed Fed announcements. At the same time, slow traders who provide liquidity experience large trading losses immediately after BoJ announcements, while they realize trading profits after Fed announcements. This heightened risk of adverse selection of slow liquidity providers by faster traders then likely exacerbates the magnitude of the illiquidity observed in the market ahead of BoJ announcements.

We note that the study of the market's reaction to the BoJ's announcements provides us with an unusual, and therefore potentially important, example of illiquidity seemingly causing an increase in volatility without new information being released. In that context, the heightened sensitivity of volatility to illiquidity observed for an extended period ahead of BoJ announcements is also notable.

Our study yields several important lessons. Most directly related to the practice of central banking, and to the impact of economic data releases more generally, we show that releasing important information on a pre-scheduled date but at a random time is likely to have undesirable consequences for market quality. The Bank of Japan introduced this method to release its policy decisions in 2001, with the goal to reduce the risk of information leakage and avoid giving an advantage to certain market participants. But the BoJ's random release time now seems to result in an unnecessarily long period of illiquidity and volatility, and it may favor a particular class of market participants.[21] More broadly, our findings clearly have implications for other financial markets where important information is expected but the exact timing of the release is not known. Finally, these results highlight again the complexity of the interaction between fast and slow traders in modern financial markets, including the potential for a negative impact on market quality under certain circumstances.

[21]We note that in 2001, when the BoJ began to use a random release time for its monetary policy decision, it faced a very different environment in the foreign exchange market. Algorithmic trading was not allowed on the EBS platform until 2004. And HFTs, as non-banks, only began trading there in 2005.

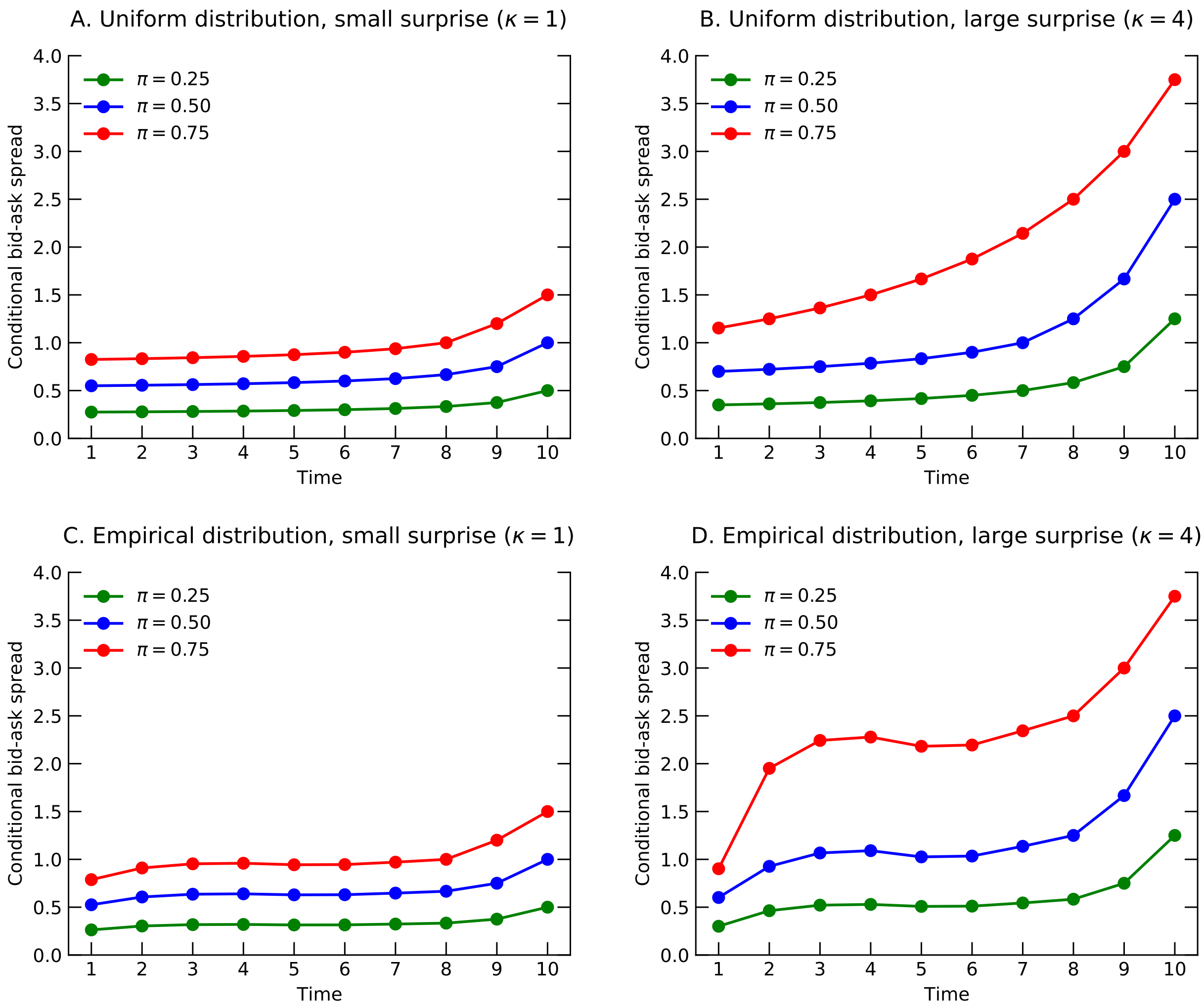
Figure 1: BoJ Release Times



Notes: The figure shows the number of BoJ statements that were released in a particular 30-minute interval during the sample period from October 2012 to December 2017. Time is in Japan Standard Time (JST). In total there were 62 statements released in this sample period (we drop one announcement due to abnormal illiquidity early in the day). The earliest released announcement time is 11:40 a.m. JST, the latest released announcement time is 2:46 p.m. JST, and the median release time is 12:15 a.m. JST.

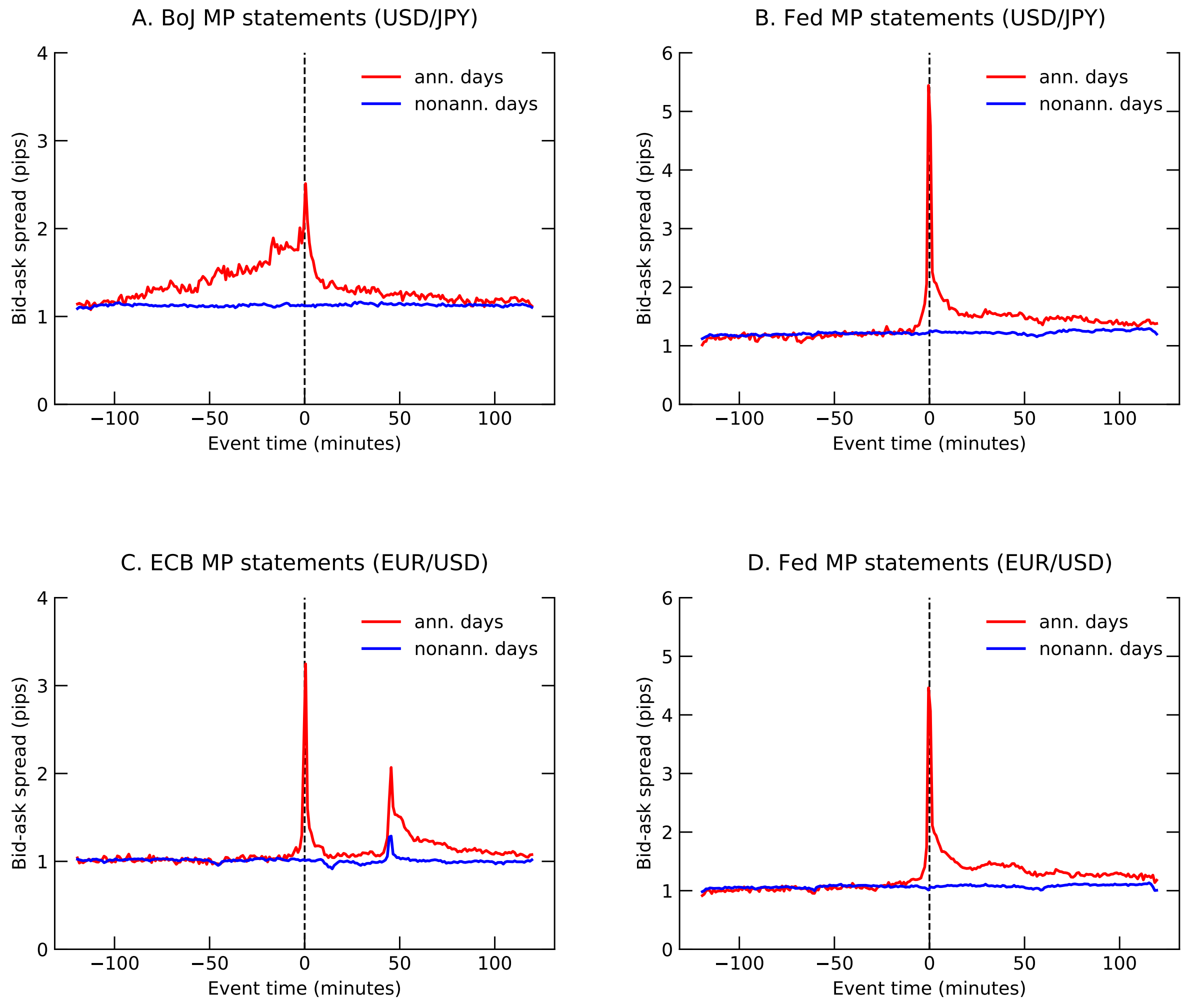
Source: Authors' calculations based on Bank of Japan website `https://www.boj.or.jp/en/mopo/mpmsche_minu/past.htm/`.

Figure 2: Theoretical Bid-Ask Spread Illustration



Notes: The figure shows theoretical bid-ask spread s_t conditional on $\tau \geq t$ according to the model described in section 2. In panels A and B, τ is uniformly distributed and in panels C and D it follows a distribution roughly similar to the empirical one for BoJ announcements. The volatility parameter ω is set to 1 throughout. Source: Authors' simulations.

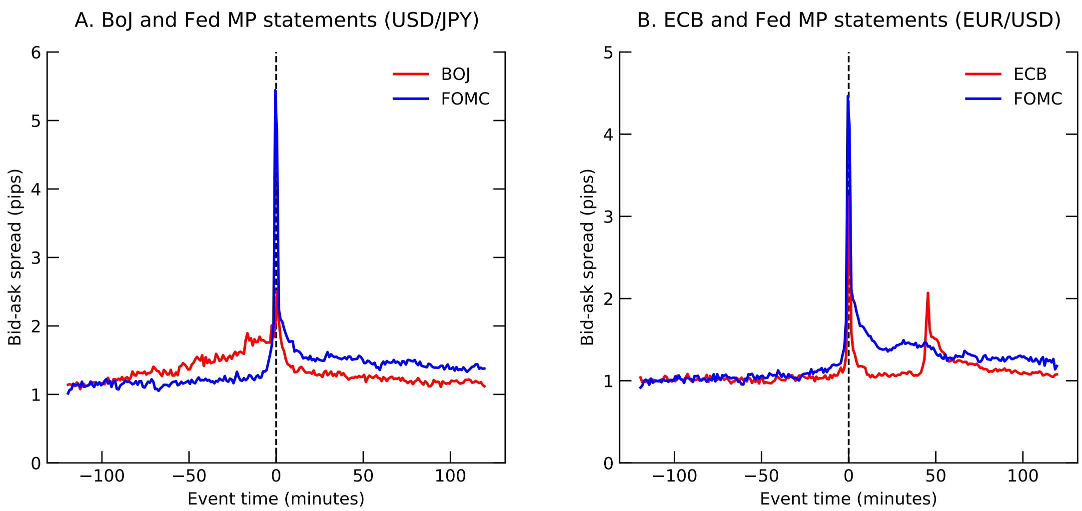
Figure 3: Bid-Ask Spreads During the Release of Different Central Bank MP Statements: Comparison Announcement with Non-Announcement Days



Notes: The figure shows average bid-ask spreads during the release of different central bank monetary policy statements. The sample period is from October 2012 to December 2017. Panel A shows the estimates for BoJ releases and uses the USD/JPY currency pair. Panel B shows the estimates for ECB releases and uses the EUR/USD currency pair. Panel C shows the estimates for Fed releases and uses the USD/JPY currency pair. Panel D shows the estimates for Fed release and uses the EUR/USD currency pair. A vertical dashed line marks the minute the statement is released to the public.

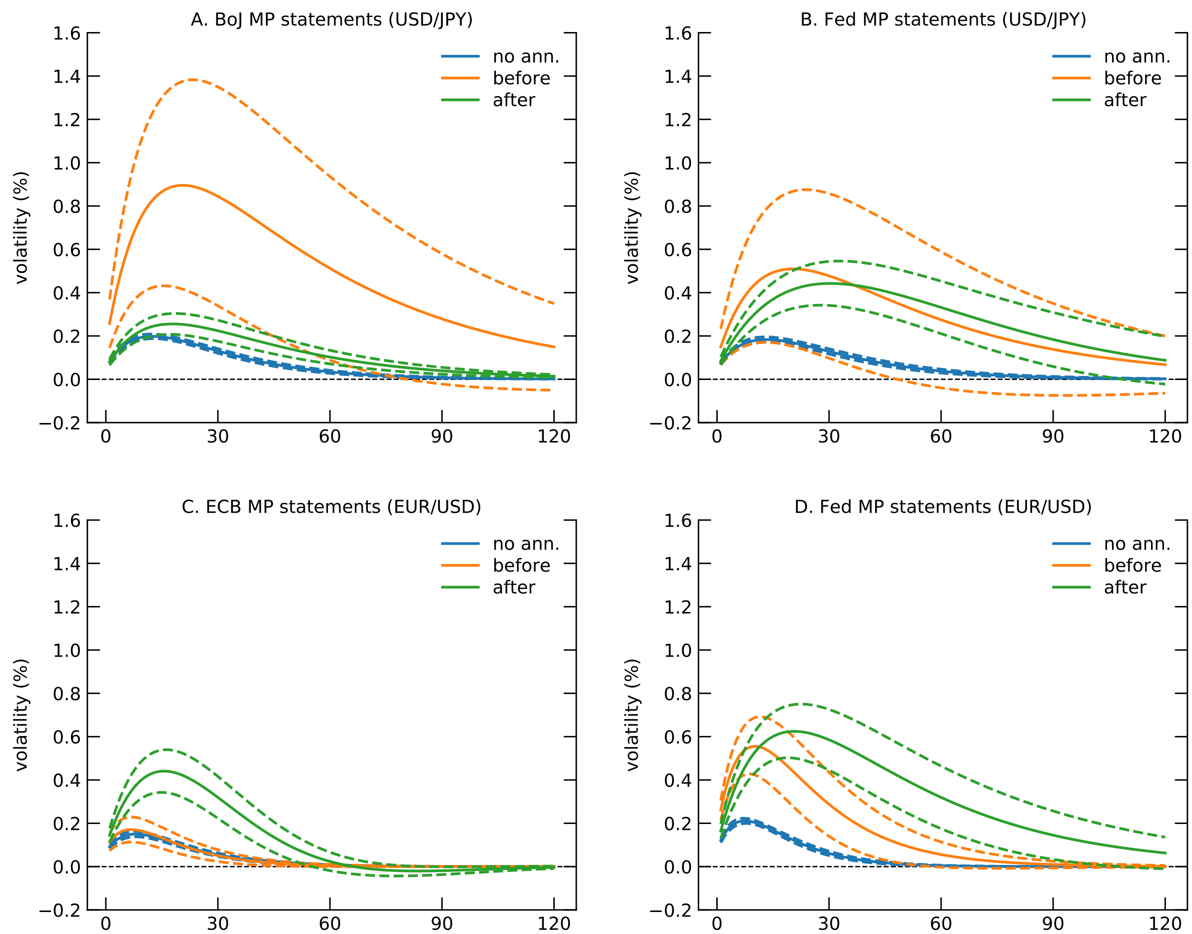
Sources: Authors' calculations based on EBS data.

Figure 4: Bid-Ask Spreads During the Release of Different Central Bank MP Statements: Comparison Across Central Banks



Notes: The figure shows average bid-ask spreads during the release of different central bank MP statements. The sample period is from October 2012 to December 2017. Panel (a) shows estimates for the release of BoJ and ECB MP statements. Panel (b) shows the estimates for the release of Fed MP statements. A vertical red line marks the minute the statement is released to the public. Sources: Authors' calculations based on EBS data.

Figure 5: Impulse Response Function: BoJ and Fed Announcement Comparison



Notes: This figure shows the impulse response of BoJ and Fed announcements. We show the response of volatility to a shock in illiquidity. The orange solid line is the response during the hour before the announcement, the green solid line is the response during the hour after the announcement, and the solid blue line is the response during non-announcement days. Dashed lines of corresponding colors are the 95 percent confidence interval bands.

Table 1: Summary Statistics: Central Bank Announcement Surprises, Implied Volatility and BoJ Release Time

	(1) Obs	(2) Mean	(3) Stdev	(4) Min	(5) Max
			Fed		
10-Year US Treasury Yield Change	42	-0.51	4.62	-13.5	9.24
Implied Volatility EUR/USD	42	8.26	2.16	4.66	13.5
Implied Volatility USD/JPY	42	9.82	2.44	5.15	15.9
			ECB		
10-Year German Bond Yield Change	50	0.00	1.37	-4.81	4.81
10-Year Italian Bond Yield Change	50	-0.77	2.49	-8.71	4.12
Implied Volatility EUR/USD	50	8.34	2.02	4.32	13.0
			BoJ		
10-Year Japanese Bond Yield Change	61	-0.03	1.25	-3.99	4.56
Implied Volatility USD/JPY	61	9.51	2.40	4.78	15.4
BoJ Release Time	61	0.86	0.62	0.18	3.27

Notes: The table shows summary statistics for government bond yield changes over a narrow window around monetary policy announcements (Fed, ECB and BoJ); 1-month implied volatility for EUR/USD and USD/JPY currency pairs on the business days prior to announcements; and the BoJ announcement time in hours from 11:30 a.m. JST. The yield changes are calculated from interest-rate futures prices 15 minutes before the announcement and 15 minutes afterwards using a duration-based approximation. The futures contracts used are the near-term (front) 10-year Japanese Government Bond futures (JGB); 10-year German government bond futures (Euro-Bund); 10-year Italian government bond futures (Euro-BTP); 10-year U.S. Treasury futures (UST). The sample period is from October 2012 to December 2017.

Sources: Authors' calculations based on Bloomberg and Thomson Reuters data.

Table 2: Correlation: Central Bank Announcement Surprises, Implied Volatility and BoJ Release Time

	(1)	(2)	(3)
		Fed	
	$|\Delta$10Y UST Yield$|$	Implied Volatility EUR/USD	Implied Volatility USD/JPY
$|\Delta$10-Year UST Yield$|$	1.00		
Implied Volatility EUR/USD	0.26	1.00	
Implied Volatility USD/JPY	0.16	0.35	1.00
		ECB	
	$|\Delta$10Y Bund Yield$|$	$|\Delta$10Y Italy Yield$|$	Implied Volatility EUR/USD
$|\Delta$10-Year German Bund Yield$|$	1.00		
$|\Delta$10-Year Italian Bond Yield$|$	0.64	1.00	
Implied Volatility EUR/USD	0.01	0.11	1.00
		BoJ	
	$|\Delta$10Y JGB Yield$|$	Implied Volatility USD/JPY	BoJ Release Time
$|\Delta$10-Year Japanese Bond Yield$|$	1.00		
Implied Volatility USD/JPY	0.41	1.00	
BoJ Release Time	0.21	-0.04	1.00

Notes: The table shows correlations for the absolute value of government bond yield changes over a narrow window around monetary policy announcements (Fed, ECB and BoJ); 1-month implied volatility for EUR/USD and USD/JPY currency pairs on the business days prior to announcements; and the BoJ announcement time in hours from 11:30 a.m. Tokyo time. The yield changes are calculated from interest-rate futures prices 15 minutes before the announcement and 15 minutes afterwards using a duration-based approximation. The futures contracts used are the near-term (front) 10-year Japanese Government Bond futures (JGB); 10-year German government bond futures (Euro-Bund); 10-year Italian government bond futures (Euro-BTP); 10-year U.S. Treasury futures (UST). The sample period is from October 2012 to December 2017.

Sources: Authors' calculations based on Bloomberg and Thomson Reuters data.

Table 3: Effect of BoJ and Fed Announcements on USD/JPY Liquidity

	One hour before				One minute before				One minute after			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ann^{BoJ}	0.338***	-0.716***	0.122	-0.932***	0.473***	-0.544***	0.368**	-0.649***	0.674***	-0.334***	0.498***	-0.510***
	(0.055)	(0.058)	(0.096)	(0.095)	(0.079)	(0.098)	(0.168)	(0.170)	(0.080)	(0.100)	(0.155)	(0.152)
$NAnn^{BoJ}$	0.099***	-0.961***	0.099***	-0.961***	0.079***	-0.943***	0.079***	-0.943***	0.076***	-0.938***	0.076***	-0.938***
	(0.008)	(0.040)	(0.008)	(0.039)	(0.011)	(0.076)	(0.011)	(0.075)	(0.012)	(0.078)	(0.012)	(0.077)
Ann^{Fed}	0.203***	-0.867***	0.203***	-0.867***	1.511***	0.479***	1.511***	0.479***	1.453***	0.429***	1.453***	0.429***
	(0.031)	(0.047)	(0.031)	(0.046)	(0.092)	(0.110)	(0.092)	(0.110)	(0.068)	(0.098)	(0.068)	(0.097)
$NAnn^{Fed}$	0.176***	-0.898***	0.176***	-0.898***	0.169***	-0.866***	0.169***	-0.866***	0.189***	-0.838***	0.189***	-0.838***
	(0.010)	(0.042)	(0.010)	(0.041)	(0.013)	(0.077)	(0.013)	(0.077)	(0.014)	(0.079)	(0.014)	(0.078)
Log(USD/JPY imp. vol.)		0.475***		0.475***		0.458***		0.458***		0.454***		0.454***
		(0.018)		(0.017)		(0.033)		(0.033)		(0.034)		(0.034)
Log(1 + BoJ release time)			0.375*	0.375**			0.182	0.182			0.306	0.306
			(0.196)	(0.182)			(0.261)	(0.245)			(0.239)	(0.227)
Adjusted R^2	0.072	0.375	0.084	0.388	0.431	0.509	0.431	0.509	0.438	0.514	0.440	0.516
Observations	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127
$D_1 = \beta_A^{BoJ} - \beta_{NA}^{BoJ}$	0.239***	0.245***	0.023	0.029	0.394***	0.399***	0.289*	0.294*	0.598***	0.604***	0.422***	0.428***
	(4.285)	(4.755)	(0.243)	(0.349)	(4.956)	(5.321)	(1.713)	(1.876)	(7.406)	(7.848)	(2.707)	(2.979)
$D_2 = \beta_A^{Fed} - \beta_{NA}^{Fed}$	0.028	0.031	0.028	0.031	1.342***	1.345***	1.342***	1.345***	1.264***	1.267***	1.264***	1.267***
	(0.853)	(1.278)	(0.852)	(1.278)	(14.49)	(15.58)	(14.48)	(15.57)	(18.12)	(19.50)	(18.11)	(19.50)
$D_1 - D_2$	0.211***	0.214***	-0.004	-0.002	-0.949***	-0.946***	-1.053***	-1.051***	-0.666***	-0.663***	-0.842***	-0.839***
	(3.269)	(3.754)	(-0.044)	(-0.024)	(-7.774)	(-8.278)	(-5.476)	(-5.870)	(-6.237)	(-6.592)	(-4.926)	(-5.329)

Notes: The table shows regression coefficients in a regression of the log of the average bid-ask spreads in the dollar-yen exchange rate one hour before, one minute before, or one minute after BoJ and Fed announcements on the BoJ and Fed announcement and non-announcement dummies, log of dollar-yen implied volatility the day before the BoJ and Fed announcements, and log of one plus BoJ release time. The BoJ announcement release time is measured in hours from 11:30 a.m. JST to the announcement time. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Sources: Authors' calculations based on EBS and Bloomberg data.

Table 4: Effect of BoJ and Fed Announcements on USD/JPY Realized Volatility

	One hour before				One minute before				One minute after			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Ann^{BoJ}	0.263***	-2.375***	-0.139	-2.777***	0.530***	-0.547***	0.511***	-0.566***	2.052***	0.754***	1.196***	-0.103
	(0.076)	(0.117)	(0.155)	(0.134)	(0.055)	(0.114)	(0.113)	(0.140)	(0.159)	(0.188)	(0.313)	(0.285)
$NAnn^{BoJ}$	0.018	-2.635***	0.018	-2.635***	0.470***	-0.613***	0.470***	-0.613***	0.465***	-0.841***	0.465***	-0.841***
	(0.019)	(0.099)	(0.019)	(0.099)	(0.016)	(0.102)	(0.016)	(0.102)	(0.016)	(0.124)	(0.016)	(0.122)
Ann^{Fed}	0.236***	-2.443***	0.236***	-2.443***	1.364***	0.271*	1.364***	0.271*	2.617***	1.299***	2.617***	1.299***
	(0.046)	(0.108)	(0.046)	(0.108)	(0.109)	(0.145)	(0.109)	(0.145)	(0.152)	(0.203)	(0.152)	(0.202)
$NAnn^{Fed}$	0.173***	-2.513***	0.173***	-2.513***	0.566***	-0.530***	0.566***	-0.530***	0.618***	-0.704***	0.618***	-0.704***
	(0.025)	(0.101)	(0.025)	(0.100)	(0.023)	(0.103)	(0.023)	(0.103)	(0.022)	(0.124)	(0.022)	(0.122)
Log(USD/JPY imp. vol.)		1.189***		1.189***		0.485***		0.485***		0.585***		0.585***
		(0.045)		(0.044)		(0.047)		(0.047)		(0.056)		(0.055)
Log(1 + BoJ Release Time)			0.698***	0.698***			0.033	0.033			1.489***	1.489***
			(0.258)	(0.170)			(0.199)	(0.184)			(0.455)	(0.434)
Adjusted R^2	0.030	0.423	0.039	0.432	0.127	0.198	0.126	0.197	0.488	0.528	0.505	0.546
Observations	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127	1,127
$D1 = \beta_A^{BoJ} - \beta_{NA}^{BoJ}$	0.245***	0.259***	-0.157	-0.142	0.060	0.066	0.041	0.047	1.588***	1.595***	0.731**	0.738**
	(3.146)	(4.208)	(-1.003)	(-1.570)	(1.058)	(1.212)	(0.360)	(0.456)	(9.937)	(10.39)	(2.331)	(2.527)
$D2 = \beta_A^{Fed} - \beta_{NA}^{Fed}$	0.063	0.071	0.063	0.071	0.798***	0.801***	0.798***	0.801***	1.999***	2.003***	1.999***	2.003***
	(1.198)	(1.491)	(1.198)	(1.490)	(7.149)	(7.510)	(7.146)	(7.507)	(12.99)	(13.31)	(12.99)	(13.30)
$D1 - D2$	0.182*	0.188**	-0.219	-0.213**	-0.737***	-0.735***	-0.757***	-0.754***	-0.411*	-0.408*	-1.268***	-1.265***
	(1.946)	(2.423)	(-1.331)	(-2.082)	(-5.883)	(-6.133)	(-4.730)	(-5.085)	(-1.853)	(-1.899)	(-3.631)	(-3.851)

Notes: The table shows regression coefficients in a regression of the log of realized volatility in the dollar-yen exchange rate one hour before, one minute before, or one minute after BoJ and Fed announcements on the BoJ and Fed announcement and non-announcement dummies, log of dollar-yen implied volatility the day before the BoJ and Fed announcements, and log of one plus BoJ release time. The BoJ announcement release time is measured in hours from 11:30 a.m. JST to the announcement time. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Authors' calculations based on EBS and Bloomberg data.

Table 5: Bivariate System of Equations for Illiquidity and Volatility

	USD/JPY			EUR/USD		
	BoJ	Fed	BoJ−Fed	ECB	Fed	ECB−Fed
ψ_{t-1}	0.897***	0.860***	0.036***	0.743***	0.881***	-0.138***
	(0.004)	(0.005)	(0.006)	(0.009)	(0.006)	(0.010)
D_t^n	0.010***	0.016***	-0.006***	0.011***	0.009***	0.002**
	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
D_t^b	0.019***	0.036***	-0.018***	0.020***	0.039***	-0.019***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)
D_t^a	0.018***	0.007*	0.011***	0.022***	0.015***	0.007
	(0.001)	(0.004)	(0.004)	(0.002)	(0.005)	(0.006)
$D_t^n \log(s_{t-1})$	0.069***	0.063***	0.006	0.087***	0.117***	-0.030***
	(0.003)	(0.003)	(0.004)	(0.005)	(0.005)	(0.007)
$D_t^n \log(\sigma_{t-1})$	0.034***	0.061***	-0.027***	0.159***	0.009***	0.149***
	(0.001)	(0.002)	(0.002)	(0.005)	(0.000)	(0.005)
$D_t^b \log(s_{t-1})$	0.092***	0.071***	0.021**	0.099***	0.198***	-0.100***
	(0.005)	(0.008)	(0.010)	(0.018)	(0.013)	(0.022)
$D_t^b \log(\sigma_{t-1})$	0.036***	0.076***	-0.040***	0.129***	0.011***	0.118***
	(0.003)	(0.004)	(0.005)	(0.010)	(0.001)	(0.010)
$D_t^a \log(s_{t-1})$	0.065***	0.072***	-0.007	0.134***	0.131***	0.003
	(0.006)	(0.008)	(0.010)	(0.014)	(0.013)	(0.020)
$D_t^a \log(\sigma_{t-1})$	0.061***	0.119***	-0.058***	0.203***	0.081***	0.122***
	(0.003)	(0.005)	(0.006)	(0.009)	(0.008)	(0.012)

Notes: The table shows parameter estimates for the volatility equation of the log-ACD(1,1) in equation (16). The left panel shows the estimates for BoJ and Fed and the difference between the two in the USD/JPY market and the right panel shows the estimates for ECB and Fed and the difference between the two in the EUR/USD market. Quasi-maximum likelihood standard errors are reported in parentheses. The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Table 6: Effect of BoJ and Fed Announcements on USD/JPY Trading Profits

	Panel A: Liquidity Demand Profits			Panel B: Liquidity Supply Profits		
	Taker is			Maker is		
	HFT	Bank Algo	Manual	HFT	Bank Algo	Manual
	(1)	(2)	(3)	(4)	(5)	(6)
Ann^{BoJ}	1.187***	0.879***	-0.912***	-0.429**	-0.056	-1.422***
	(0.180)	(0.247)	(0.209)	(0.194)	(0.240)	(0.214)
$NAnn^{BoJ}$	0.051***	0.033*	-0.015	-0.007	0.022	-0.086***
	(0.015)	(0.019)	(0.021)	(0.019)	(0.015)	(0.019)
Ann^{Fed}	0.237*	-0.182	-1.593***	0.112	-0.071	0.494***
	(0.129)	(0.154)	(0.180)	(0.137)	(0.152)	(0.182)
$NAnn^{Fed}$	0.201***	-0.192***	-0.217***	-0.045	-0.079	0.043
	(0.045)	(0.051)	(0.073)	(0.054)	(0.054)	(0.053)
Adjusted R^2	0.002	0.001	0.003	0.0001	0.0001	0.005
Observations	18,878	11,910	7,213	14,340	12,040	11,621
$D1 = \beta_A^{D,BoJ} - \beta_{NA}^{D,BoJ}$	1.136***	0.846***	-0.898***	-0.422**	-0.078	-1.336***
	(6.306)	(3.416)	(-4.279)	(-2.168)	(-0.323)	(-6.220)
$D2 = \beta_A^{D,Fed} - \beta_{NA}^{D,Fed}$	0.036	0.009	-1.377***	0.157	0.009	0.451**
	(0.266)	(0.057)	(-7.076)	(1.068)	(0.053)	(2.379)
$D1 - D2$	1.100***	0.837***	0.479*	-0.579**	-0.086	-1.787***
	(4.858)	(2.826)	(1.674)	(-2.373)	(-0.298)	(-6.238)

Notes: The table shows regression coefficients in a regression of the liquidity demand profits (panel A) and liquidity provision profits (panel B) by different market participants during the minute after the release of monetary policy statements by the BoJ and Fed on the BoJ and Fed announcement and non-announcement dummies. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

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APPENDIX

A Central Bank Statements and Press Conferences

We collect the timestamps and release dates of the central bank statements and press conferences from various official sources. All our timestamps are at the minutely precision.

The dates and times of the Federal Open Market Committee (FOMC) meetings (with or without press conferences) are available on the official Federal Reserve website (`https://www.federalreserve.gov/monetarypolicy`).

For the ECB meetings, the dates of the monetary decisions are parsed from the official ECB website (`https://www.ecb.europa.eu/press/pr/html/index.en.html`). In our sample, the ECB statement is usually released at 13:45 CET, while the ECB press conference starts at 14:30 CET.

The times of the Bank of Japan monetary policy statements are extracted programmatically from the pdfs available on the BoJ website (`https://www.boj.or.jp/en/mopo/mpmsche_minu/past.htm/`). The (random) time of the release is either available somewhere at the end of the pdf (among various official release times) or embedded in the metadata of the pdfs themselves.

B Impulse Response Function

In sections 4.4.1 and 4.4.2 we describe our specification for the joint dynamics of illiquidity and volatility. We use a log-ACD(1,1) specification, which is non-linear, and the impulse response function therefore depends on the initial conditions and shock size. We follow Manganelli (2005) who derives an impulse response function for a standard ACD model, $\partial \mathbb{E}(\boldsymbol{\psi}_t|\Omega_0)/\partial \boldsymbol{\varepsilon}_0{}'$, $t \geq 0$, and assume that the system is initially at a steady state. Our case is more involved, however, given the additional nonlinearity of the log-ACD specification, as we need to derive $\partial \mathbb{E}(\exp(\boldsymbol{\psi}_t)|\Omega_0, \boldsymbol{\varepsilon}_1 = \cdots = \boldsymbol{\varepsilon}_t = \boldsymbol{\imath})/\partial \boldsymbol{\varepsilon}_0{}'$, $t \geq 0$ and chose at which value of $\boldsymbol{\varepsilon}_0$ to evaluate the impulse response function.

Suppose that the system in 14 is in a steady state up to time 0, i.e. $\boldsymbol{\varepsilon}_t = \boldsymbol{\imath}$ and $\log \boldsymbol{y}_t = \boldsymbol{\psi}_t = \bar{\boldsymbol{\psi}}$ for all $t < 0$, (dropping the subscript i for simplicity and using t to denote time). Then $\bar{\boldsymbol{\psi}} = (\boldsymbol{I} - \boldsymbol{A}_1 - \boldsymbol{B})^{-1}\boldsymbol{\omega}$. Starting with the immediate impact of a shock at time 0, i.e. the impulse response function at $t = 0$, we have

$$\boldsymbol{\psi}_0 = \bar{\boldsymbol{\psi}} + \boldsymbol{A}_0 \log \boldsymbol{\varepsilon}_0. \tag{22}$$

Taking expectation conditional on the information at time 0, Ω_0, we have

$$\mathbb{E}(\exp(\boldsymbol{\psi}_0)|\Omega_0) = \exp(\bar{\boldsymbol{\psi}}) \odot \exp(\boldsymbol{A}_0 \log \boldsymbol{\varepsilon}_0). \tag{23}$$

The derivative of the above expectation depends on $\boldsymbol{\varepsilon}_0$, unlike in the standard ACD case. It is natural to evaluate the derivative at $\boldsymbol{\varepsilon}_0 = \boldsymbol{\imath}$, i.e. to perturb the system around its steady state. The impulse response function at $t = 0$ is then given by

$$\left.\frac{\partial \mathbb{E}(\exp(\boldsymbol{\psi}_0)|\Omega_0)}{\partial \boldsymbol{\varepsilon}_0'}\right|_{\boldsymbol{\varepsilon}_0 = \boldsymbol{\imath}} = \boldsymbol{A}_0 \text{diag}(\exp(\bar{\boldsymbol{\psi}})) \tag{24}$$

Turning to the case $t > 0$, by recursive substitution we obtain

$$\boldsymbol{\psi}_t = \bar{\boldsymbol{\psi}} + \boldsymbol{A}_0 \log \boldsymbol{\varepsilon}_t + \sum_{j=1}^{t-1} \left[(\boldsymbol{A}_1 + \boldsymbol{B})^{j-1} \boldsymbol{A}_1 + (\boldsymbol{A}_1 + \boldsymbol{B})^j \boldsymbol{A}_0\right] \log \boldsymbol{\varepsilon}_{t-j} + (\boldsymbol{A}_1 + \boldsymbol{B})^{t-1} \boldsymbol{A}_1 \log \boldsymbol{\varepsilon}_0. \tag{25}$$

Taking conditional expectations under the assumption that all future shocks ($t > 0$) are equal to their stead-state value of one gives

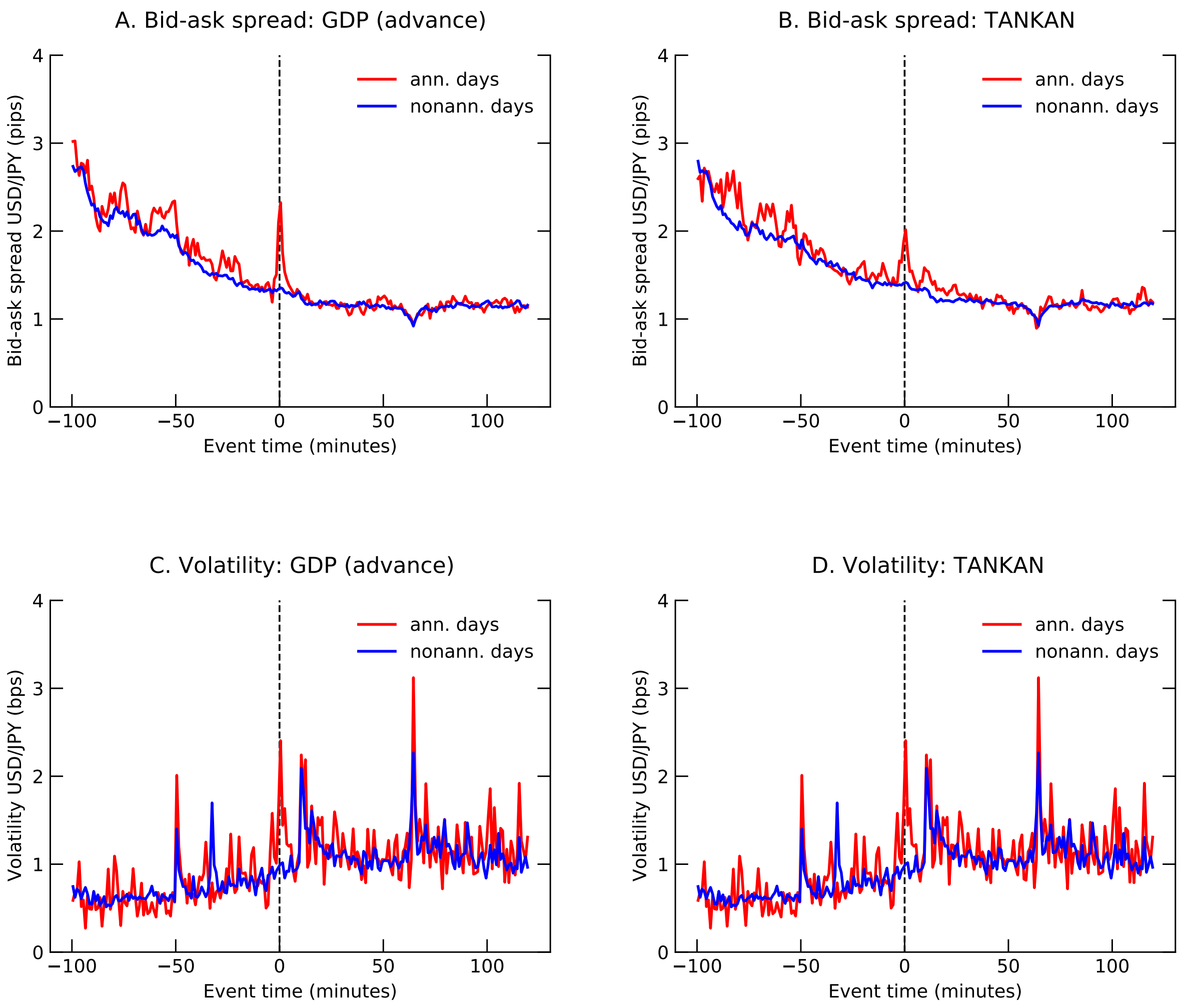
$$\mathbb{E}(\exp(\boldsymbol{\psi}_0)|\Omega_0, \boldsymbol{\varepsilon}_1 = \cdots = \boldsymbol{\varepsilon}_t = \boldsymbol{\imath}) = \exp(\bar{\boldsymbol{\psi}}) \odot \exp((\boldsymbol{A}_1 + \boldsymbol{B})^{t-1} \boldsymbol{A}_1 \log \boldsymbol{\varepsilon}_0). \tag{26}$$

and differentiating w.r.t. $\boldsymbol{\varepsilon}_0$ and evaluating at $\boldsymbol{\varepsilon}_0 = \boldsymbol{\imath}$ yields

$$\left.\frac{\partial \mathbb{E}(\exp(\boldsymbol{\psi}_t)|\Omega_0, \boldsymbol{\varepsilon}_1 = \cdots = \boldsymbol{\varepsilon}_t = \boldsymbol{\imath})}{\partial \boldsymbol{\varepsilon}_0'}\right|_{\boldsymbol{\varepsilon}_0 = \boldsymbol{\imath}} = (\boldsymbol{A}_1 + \boldsymbol{B})^{t-1} \boldsymbol{A}_1 \text{diag}(\exp(\bar{\boldsymbol{\psi}})). \tag{27}$$

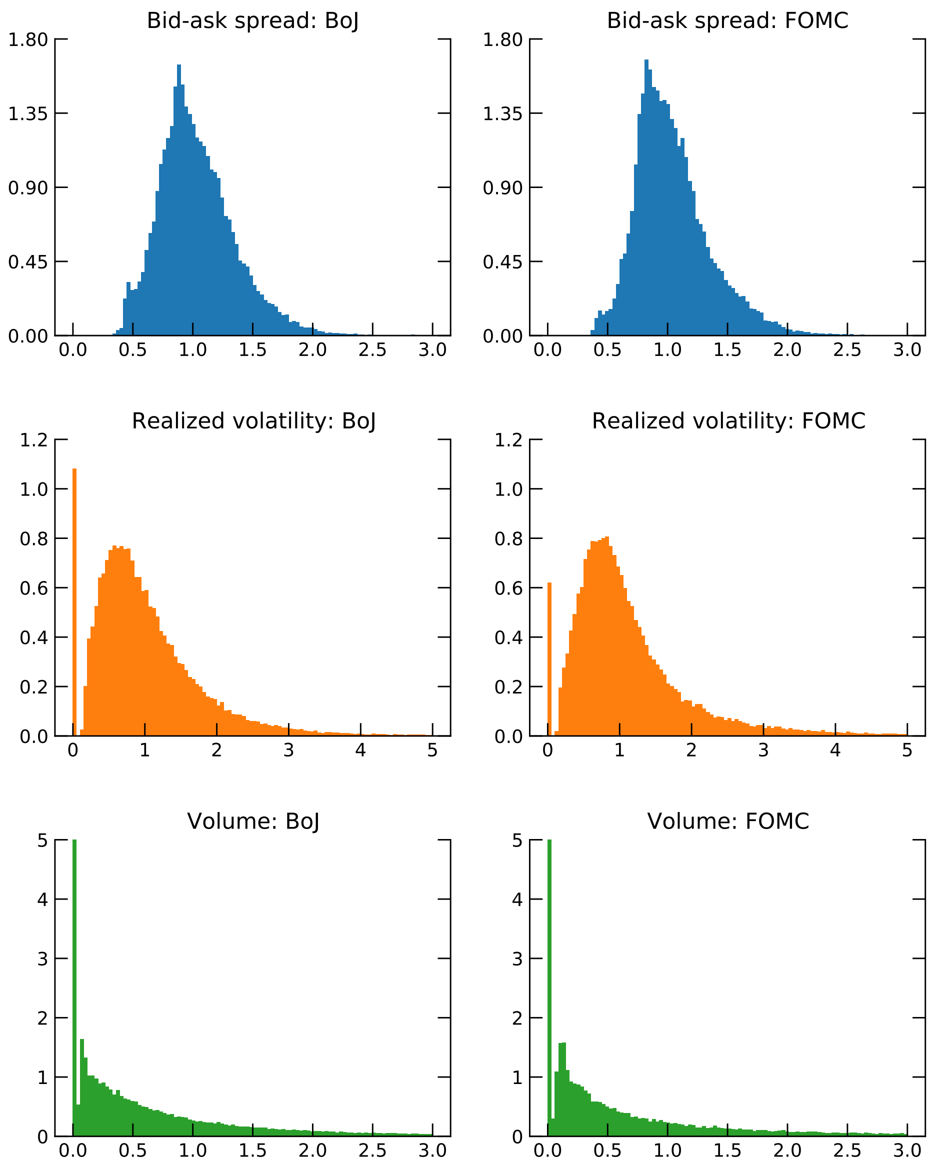
To summarize, the impulse response function measures the impact of an infinitesimal perturbation of $\boldsymbol{\varepsilon}_0$ around $\boldsymbol{\imath}$ under the assumption that the system is at a steady state at $t < 0$ and all future shocks ($t > 0$) are turned off, i.e. following the perturbation at time 0 the system gradually returns to the steady state.

Figure A1: Bid-ask Spreads and Volatility around Japanese Macroeconomic Announcements



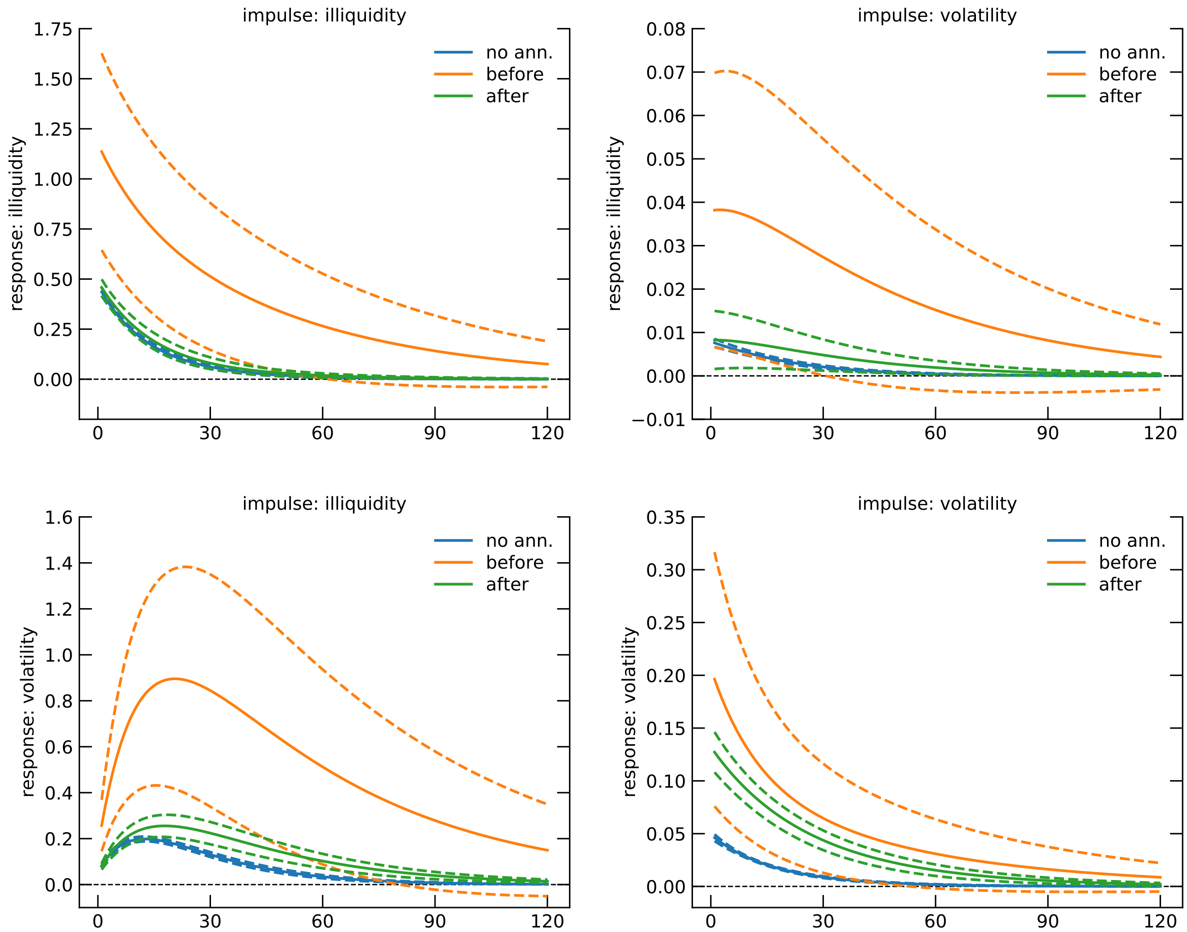
Notes: This figure shows the average bid-ask spread and volatility for the USD/JPY currency pair around Japanese macroeconomic announcements. The sample period is from October 2012 to December 2017. Panels A and C show the bid-ask spread and volatility, respectively, for the GDP announcements, and Panels B and D the bid-ask spread and volatility, respectively, for the TANKAN announcements.

Figure A2: Histogram of Key USD/JPY Variables.



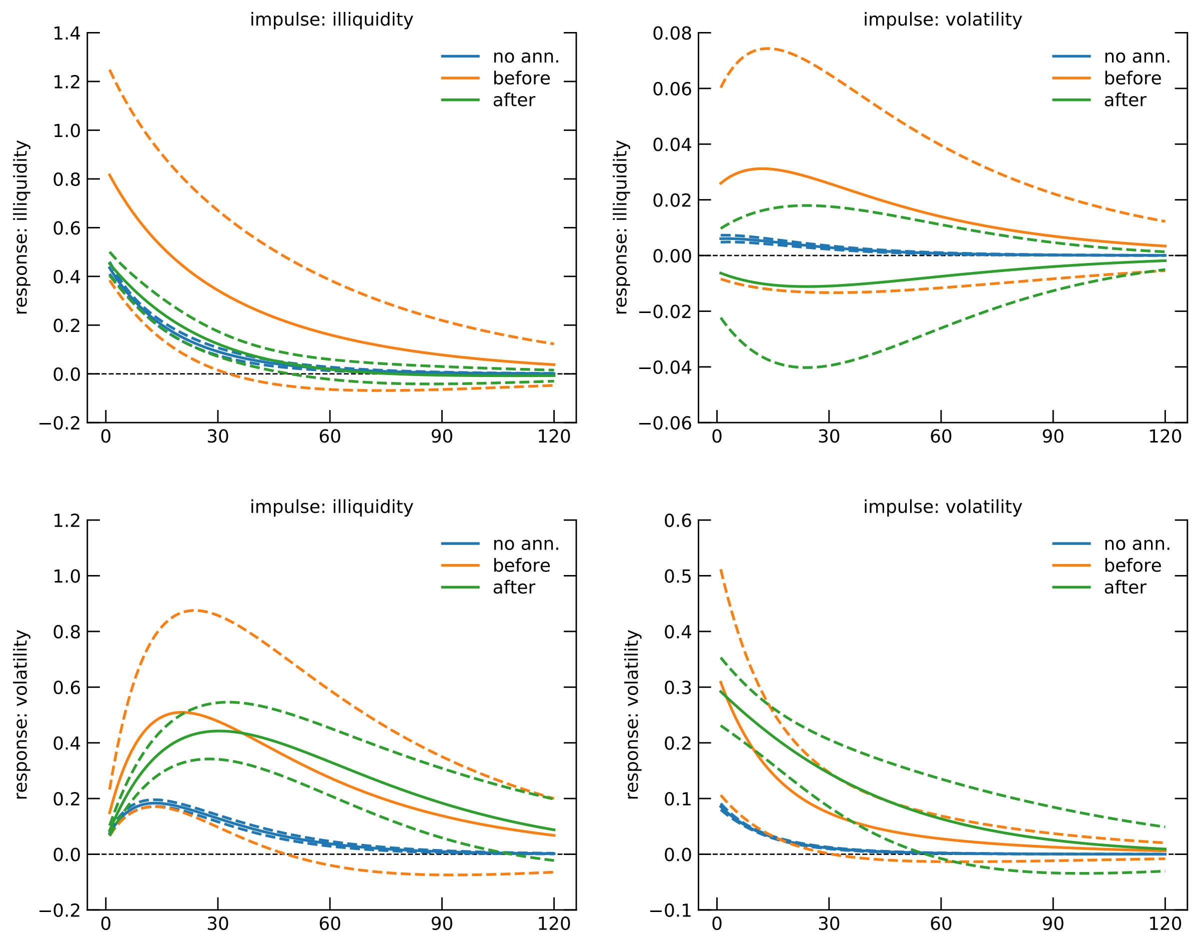
Notes: This figure shows the histograms of diurnally adjusted 1-min variables for BoJ and Fed announcements and the USD/JPY currency pair that are used in the log-ACD(1,1) model.

Figure A3: Impulse Response Function: BoJ Announcements



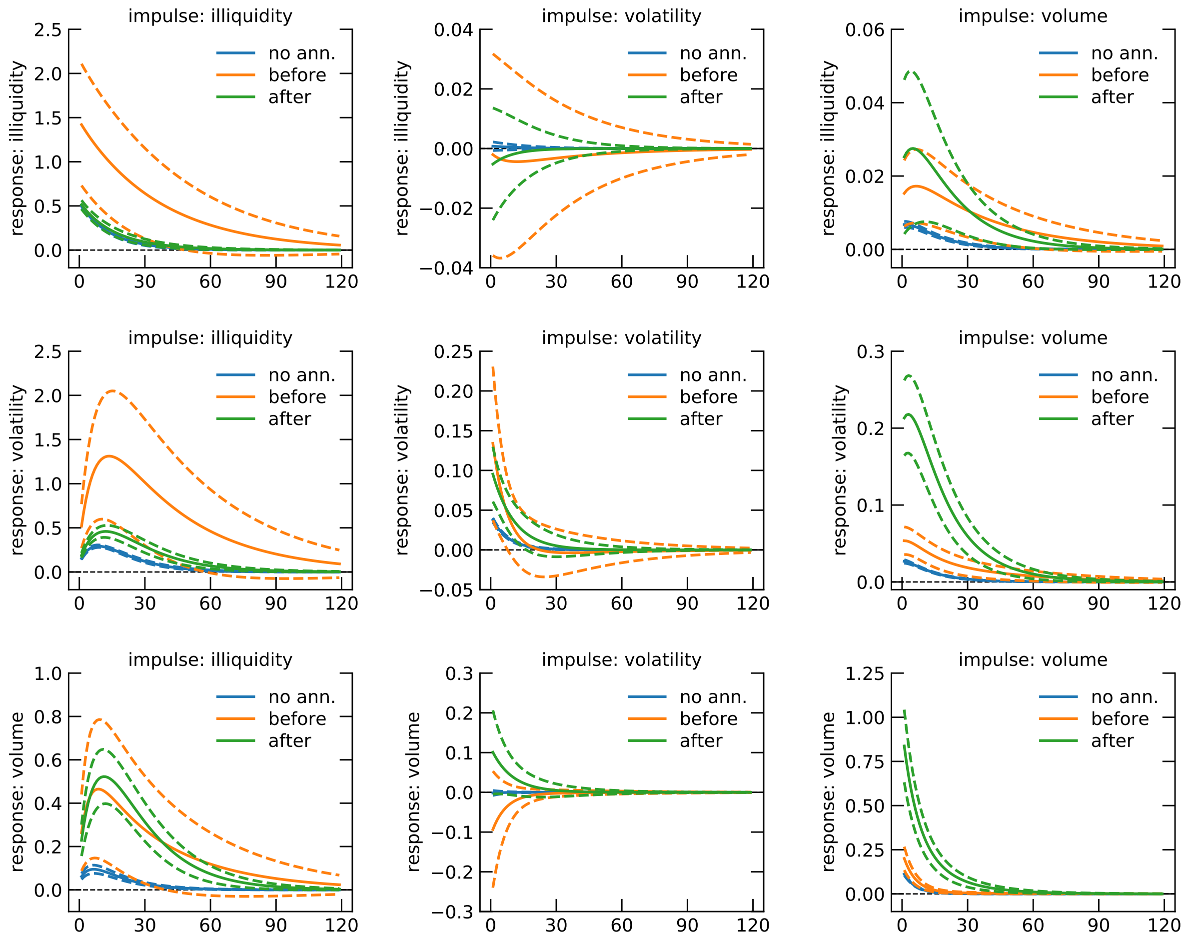
Notes: This figure shows the impulse response of the bivariate system of equations (illiquidity and volatility) explained in section 4.4.1 estimated during BoJ announcements. The orange solid line is the response during the hour before the announcement, the green solid line is the response during the hour after the announcement, and the solid blue line is the response during non-announcement days.

Figure A4: Impulse Response Function: Fed Announcements



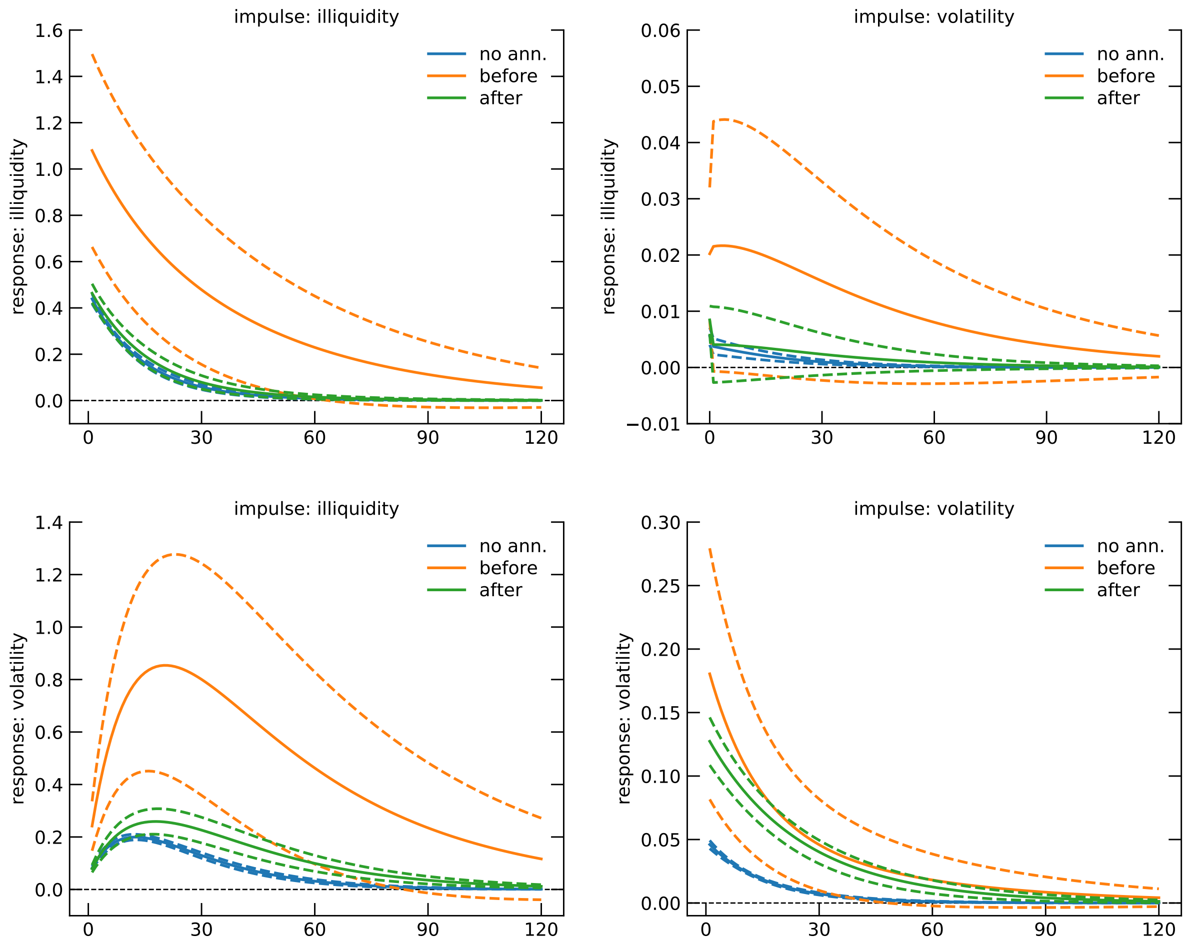
Notes: This figure shows the impulse response of the bivariate system of equations (illiquidity and volatility) explained in section 4.4.1 estimated during Fed announcements. The orange solid line is the response during the hour before the announcement, the green solid line is the response during the hour after the announcement, and the solid blue line is the response during non-announcement days.

Figure A5: Impulse Response Function: BoJ Announcements, Three Variable System



Notes: This figure shows the impulse response the trivariate system of equations (illiquidity, volatility, and trading volume) explained in section 4.4.1 estimated during BoJ announcements. We show the response of volatility to a shock in illiquidity. The orange solid line is the response during the hour before the announcement, the green solid line is the response during the hour after the announcement, and the solid blue line is the response during non-announcement days. Dashed lines of corresponding colors are the 95 percent confidence interval bands.

Figure A6: Impulse Response Function: BoJ Announcements, Contemporaneous Effects



Notes: This figure shows the impulse response of the bivariate system of equations (illiquidity and volatility) explained in section 4.4.1 estimated during BoJ announcements. The orange solid line is the response during the hour before the announcement, the green solid line is the response during the hour after the announcement, and the solid blue line is the response during non-announcement days.

Table A1: Effect of ECB and Fed Announcements on EUR/USD Liquidity

	One hour before		One minute before		One minute after	
	(1)	(2)	(3)	(4)	(5)	(6)
Ann^{ECB}	0.028*	-0.769***	0.684***	-0.215**	0.987***	0.076
	(0.017)	(0.037)	(0.065)	(0.085)	(0.081)	(0.094)
$NAnn^{ECB}$	0.003	-0.792***	-0.004	-0.900***	-0.013	-0.922***
	(0.006)	(0.035)	(0.010)	(0.075)	(0.010)	(0.074)
Ann^{Fed}	0.088***	-0.705***	1.299***	0.405***	1.306***	0.400***
	(0.025)	(0.040)	(0.096)	(0.117)	(0.067)	(0.095)
$NAnn^{Fed}$	0.060***	-0.740***	-0.023*	-0.924***	0.028**	-0.885***
	(0.008)	(0.036)	(0.013)	(0.076)	(0.013)	(0.075)
Log(EUR/USD imp. vol.)		0.381***		0.429***		0.436***
		(0.017)		(0.036)		(0.035)
Adjusted R^2	0.033	0.404	0.525	0.591	0.590	0.653
Observations	1,005	1,005	1,005	1,005	1,005	1,005
$D_1 = \beta_A^{ECB} - \beta_{NA}^{ECB}$	0.025	0.023**	0.688***	0.686***	1.000***	0.998***
	(1.394)	(2.075)	(10.48)	(11.66)	(12.27)	(13.33)
$D_2 = \beta_A^{Fed} - \beta_{NA}^{Fed}$	0.028	0.034*	1.322***	1.329***	1.278***	1.285***
	(1.075)	(1.797)	(13.67)	(14.27)	(18.77)	(19.77)
$D_1 - D_2$	-0.003	-0.011	-0.634***	-0.643***	-0.278***	-0.287***
	(-0.096)	(-0.512)	(-5.420)	(-5.843)	(-2.616)	(-2.900)

Notes: The table shows regression coefficients in a regression of the log of the average bid-ask spreads in the euro-dollar exchange rate one hour before, one minute before, or one minute after ECB and Fed announcements on the ECB and Fed announcement and non-announcement dummies, log of euro-dollar implied volatility the day before the ECB and Fed announcements. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Table A2: Effect of ECB and Fed Announcements on EUR/USD Realized Volatility

	One hour before		One minute before		One minute after	
	(1)	(2)	(3)	(4)	(5)	(6)
Ann^{ECB}	0.298***	-1.990***	1.023***	0.145	1.968***	0.931***
	(0.059)	(0.107)	(0.089)	(0.159)	(0.149)	(0.197)
$NAnn^{ECB}$	0.174***	-2.108***	0.593***	-0.283**	0.629***	-0.405***
	(0.019)	(0.102)	(0.020)	(0.129)	(0.020)	(0.133)
Ann^{Fed}	0.234***	-2.041***	1.343***	0.470***	2.680***	1.649***
	(0.056)	(0.107)	(0.133)	(0.168)	(0.153)	(0.208)
$NAnn^{Fed}$	0.076***	-2.216***	0.599***	-0.281**	0.593***	-0.446***
	(0.024)	(0.105)	(0.021)	(0.129)	(0.021)	(0.135)
Log(EUR/USD imp. vol)		1.094***		0.419***		0.495***
		(0.049)		(0.062)		(0.065)
Adjusted R^2	0.016	0.381	0.114	0.156	0.470	0.498
Observations	1,005	1,005	1,005	1,005	1,005	1,005
$D_1 = \beta_A^{ECB} - \beta_{NA}^{ECB}$	0.125**	0.118***	0.430***	0.428***	1.339***	1.336***
	(2.015)	(2.592)	(4.710)	(4.824)	(8.889)	(8.915)
$D_1 = \beta_A^{Fed} - \beta_{NA}^{Fed}$	0.158***	0.175***	0.744***	0.751***	2.087***	2.095***
	(2.590)	(3.850)	(5.541)	(5.746)	(13.48)	(14.13)
$D1 - D2$	-0.034	-0.057	-0.314*	-0.323**	-0.748***	-0.759***
	(-0.386)	(-0.890)	(-1.932)	(-2.044)	(-3.463)	(-3.599)

Notes: The table shows regression coefficients in a regression of the log of realized volatility in the euro-dollar exchange rate one hour before, one minute before, or one minute after BoJ and Fed announcements on the ECB and Fed announcement and non-announcement dummies, and log of euro-dollar implied volatility the day before the BoJ and Fed announcements. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Table A3: Effect of ECB and Fed Announcements on EUR/USD Profits

	Panel A: Liquidity Demand Profits			Panel B: Liquidity Provision Profits		
	Taker is			Maker is		
	HFT	Bank Algo	Manual	HFT	Bank Algo	Manual
	(1)	(2)	(3)	(4)	(5)	(6)
Ann^{ECB}	0.747***	-0.841***	-1.444***	-0.015	0.744***	-0.522***
	(0.124)	(0.185)	(0.201)	(0.141)	(0.174)	(0.177)
$NAnn^{ECB}$	0.030**	-0.002	-0.218***	0.062***	0.029*	-0.030*
	(0.014)	(0.017)	(0.020)	(0.017)	(0.015)	(0.018)
Ann^{Fed}	1.000***	0.762***	-0.794***	-0.194**	-0.494***	-1.634***
	(0.098)	(0.121)	(0.164)	(0.097)	(0.122)	(0.153)
$NAnn^{Fed}$	0.136***	-0.070***	-0.257***	0.049**	-0.005	-0.065***
	(0.017)	(0.017)	(0.034)	(0.022)	(0.017)	(0.021)
Adjusted R^2	0.002	0.004	0.004	0.0001	0.003	0.005
Observations	29,837	18,977	8,731	22,946	19,068	15,531
$D1 = \beta_A^{D,ECB} - \beta_{NA}^{D,ECB}$	0.717***	-0.839***	-1.226***	-0.077	0.714***	-0.492***
	(5.764)	(-4.517)	(-6.063)	(-0.540)	(4.097)	(-2.771)
$D2 = \beta_A^{D,Fed} - \beta_{NA}^{D,Fed}$	0.865***	0.832***	-0.537***	-0.243**	-0.489***	-1.569***
	(8.681)	(6.796)	(-3.216)	(-2.434)	(-3.973)	(-10.140)
$D1 - D2$	-0.148	-1.670***	-0.689***	0.166	1.204***	1.077***
	(-0.928)	(-7.512)	(-2.627)	(0.955)	(5.639)	(4.575)

Notes: The table shows regression coefficients in a regression of the liquidity demand profits (panel A) and liquidity provision profits (panel B) by different market participants one-minute after the release of monetary policy statements by the ECB and Fed on the ECB and Fed announcement and non-announcement dummies. The standard errors shown in parenthesis below the coefficient estimates and the t-stats shown in parenthesis below the difference in coefficients are robust to heteroskedasticity (White, 1982). The sample period is from October 2012 to December 2017. ***, **, * denote statistical significance at the 1%, 5%, and 10% level, respectively.