Price Pressure and Efficiency on FOMC Announcements

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ABSTRACT

We examine the impact of the surge in trading activity following FOMC announcements on price discovery in the equity market, in particular in the highly liquid S&P 500 E-mini futures. In contrast to the hypothesis that all trading reflects learning about these public news announcements, we find that trading is associated with a decrease in price informativeness and order imbalances generate substantial price reversals reaching 60 basis points even at horizons of several hours. Our findings show that price pressure is prevalent in the most liquid assets following public news and have direct implications for measuring the impact of monetary policy news on equity prices.

JEL Classification: E50, G12, G14.
Keywords: FOMC announcements, market efficiency, price discovery, price pressure

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Understanding the impact of monetary policy on equity prices is of key importance for market participants and policymakers. Using Federal Open Market Committee (FOMC) announcements as an important shock to monetary policy, it is now well understood that news about interest rates at different maturities and news about risk premia are the main determinants of equity price reactions.[1]

In this paper, we ask a different question: how is the information provided by the FOMC incorporated into prices? In the simplest setting of public information in a frictionless market, liquidity providers would instantaneously adjust quotes to the new equilibrium price at the time of the announcement, and the price would remain there until more news is revealed. However, two of the most striking empirical features in equity markets around FOMC announcements are large increases in trading volume and realized volatility in the hours following the events. We aim to understand whether the trading helps market participants learn about the pricing implication of monetary policy announcements and if the increased volatility reflects information flow (Ross, 1989). The process of how information enters prices is fundamental to financial economics and remains not well understood for the important monetary policy information revealed at FOMC announcements.

Specifically, we examine whether trading increases the informational content of prices by reducing remaining uncertainty about the "true" value of assets once the initial information contained in FOMC announcements has been taken into account. Under the learning hypothesis, trading after the announcements is based on information, and other market participants rationally learn from the order flow. As a result, prices converge to the new equilibrium value as in classical microstructure models (Glosten and Milgrom, 1985, Kyle, 1985). Under this view, prices following FOMC announcements are conditional expectations

[1]Gürkaynak, Sack, and Swanson (2005b), Gorodnichenko and Weber (2016), and Swanson (2017) document the importance of interest rate changes. Kroencke, Schmeling, and Schrimpf (2018) argues that investors portfolio rebalancing affects risk premia. The evidence is not restricted to U.S. data; for example, Leombroni, Vedolin, Venter, and Whelan (2018) and Schmeling and Wagner (2017) examine high-frequency equity price changes following monetary policy announcements of the European Central Bank.

of the new equilibrium price, and they become more precise with more trading activity.

Alternatively, the large trading volume following FOMC announcements could be in response to the announcement, but unrelated to new information. For example, Kroencke, Schmeling, and Schrimpf (2018) argue that changes in investors attitude towards risk lead them to rebalance their portfolios. In this case, trading does not contribute to an increase in the informational content of prices. In a frictionless market, the trading activity would be unrelated to prices (the volume irrelevance hypothesis). More realistically, however, trading might result in price pressure, which can distort the price formation process and make prices less informative (Hendershott and Menkveld, 2014) due to inventory risk born by liquidity providers (Stoll, 1978). We call this the noise hypothesis.

To test these hypotheses, we follow Biais, Hillion, and Spatt (1999), who analyze price formation during the preopening of markets, and use unbiasedness regressions. This approach allows us to examine price formation without relying on a pre-specified measure of unexpected news, which are difficult to quantify for FOMC announcements. In particular, we interpret the S&P 500 E-mini futures (EMini) log prices 30 minutes prior to FOMC announcements and at settlement time (4:15 p.m.) on the next trading day as the fundamental prices without and with information, and label the difference the total announcement return. We then perform regressions across events of these total announcement returns onto partial announcement returns, which also start 30 minutes before the announcements, but end at time t.

For fixed t, the slope estimate β from this regression provides information about the speed at which prices incorporate the public information on average.[2] The regression R^2 measures how much of variation in total announcement returns is captured by partial announcement returns, and therefore provides information about the precision of prices at time t about

[2]In this paper, we follow the work of Brunnermeier (2005) and Weller (2018) and define "informativeness" as how informative the price process is in absolute terms and "informational efficiency" as the speed at which price adjustment occurs.

the fundamental value.[3] Estimating these regressions for different end-times t, β_t and ${R^2}_t$ describe the dynamics of price informativeness.

For the full sample of FOMC announcements from September 1997 to December 2017, we find an immediate increase in price informativeness at the announcement, as ${R^2}_t$ jumps from zero to 0.15. There is weak evidence for underreaction in the first two minutes after the announcement, but prices are approximately informationally efficient. However, in the minutes after the announcements, we find strong evidence against the learning hypothesis and in favor of the noise hypothesis. ${R^2}_t$ does not increase further during this period of high trading volume, but rather remains unchanged, and often decreases, over the 60 minutes following announcements.

Using subsamples for different time periods, we find that FOMC announcements later in the sample are associated with a higher trading volume, generally see a larger jump in ${R^2}_t$ at the announcement, and a subsequent larger decrease in price informativeness. The decrease in price informativeness is more pronounced for announcements with more anticipated news of importance. This suggests that the trading volume following FOMC announcements does not aid, but hinder, price discovery. The effects are long lasting, approximately two hours after the announcement, and even prices at the end of the trading day often contain little information about the fundamental price at the end of the next day.

If trading is indeed responsible for distorting the price discovery process, we should expect temporary price pressure on prices following announcements followed by a price reversal. To capture the event of a price reversal, we focus on a subset of FOMC announcements which we know are more newsworthy and are anticipated by investors to be more important. The announcements are those that are accompanied with a scheduled press conference by the chairperson of the Federal reserve. Since April 2011, four out of eight FOMC announce-

[3]Information contained in the slope coefficient and the R^2 are not redundant. It is possible for prices to be informationally efficient with a slope of one, implying that prices are martingale, yet not being very informative, i.e., learning about the true value is slow and R^2 is low. It is also possible for prices to be biased yet very informative, i.e., there is price under or overreaction but R^2 is high.

ments have press conferences. Boguth, Grégoire, and Martineau (2019) show that these announcements are perceived as more important by market participants. Moreover, our price formation analysis shows that these meetings are associated with the most important decrease in price informativeness. We find that returns from the 10th to the 60th minute following announcements predicts a substantial price reversal of about 60 basis points that can last several hours until the next trading day. For announcements with no press conferences, we find no price reversal.[4]

To understand if indeed trading is responsible for this price reversal, we use *accurate* signed order flow data for the SPDR S&P 500 exchange-traded fund (SPY), which we do not have for the EMini, and construct a liquidity-taking order imbalance measure to capture price pressure. Our findings of price formation and price reversal are close to identical if we use the SPY instead of the EMini. Therefore, we assume that order imbalance in the SPY mirrors the one found in the EMini. We show that the component of returns following FOMC announcements that is explained by price pressure from order imbalance explains almost all of the price reversal.

These results have important implications for policymakers and researchers attempting to understand how the stock market responds to monetary policy announcements.[5] For example, our paper shows that choosing the window length around FOMC announcements to measure at high-frequency the impact of unexpected changes in interest rates on equity prices is not an arbitrary decision. We find that unexpected changes in interest rates using eurodollars, a recent and more commonly used measure of monetary policy surprises (see Nakamura and Steinsson, 2017), largely explains returns in a two-minute window following announcements, with a R^2 of 55%. Increasing the window length from 10 to 60 minutes following the announcement significantly lowers the explanatory power and generates sta-

[4]Evidence of price reversal is also found for the underlying assets of the EMini, i.e., the S&P 500 index.

[5]Mitchell, Pulvino, and Stafford (2004) show that price pressure following mergers announcements can bias downward estimates of merger wealth.

tistically non-significant results when controlling for order flow. However, increasing the window further to 90 minutes generates statistically significant results in part due to prices becoming less noisy when the temporary price pressure dissipates.

Related literature

This paper contributes to the growing literature on price pressure and market inefficiency related to inventory risks born by intermediaries providing liquidity. Hendershott and Menkveld (2014) document large daily transitory volatility in individual stock returns due to price pressure that impede price efficiency. Kirilenko, Kyle, Samadi, and Tuzun (2017) study intraday market intermediation around the "Flash Crash" (May 6, 2010) and find that the behavior of non-designated intraday intermediaries is consistent with the theory of limited risk-bearing capacity. More closely related, Kroencke, Schmeling, and Schrimpf (2018), show that a large share of the market's reaction to FOMC news seems to be driven by changes in expected returns. This results in important differences in announcement returns between bonds and equities, and in portfolio rebalancing by investors. We depart from their analysis in two ways. First, we directly examine the impact of price pressure on equity prices following FOMC announcements. Second, we show how this price pressure can distort the price discovery process.

Our paper further contributes to the large literature on price formation following macroeconomic announcements.[6] We contribute to this literature by focusing especially on FOMC announcements. In contrast to other macroeconomic news, such as unemployment or industrial production, the speed at which FOMC announcement surprises are incorporated into stock prices remains largely elusive in the finance and macroeconomic literature.[7] Following Nakamura and Steinsson (2017), we use changes in eurodollar rates minutes following FOMC

[6]Some of the important papers include Balduzzi, Elton, and Green (2001) and Andersen, Bollerslev, Diebold, and Vega (2003), and more recent, Hu, Pan, and Wang (2017) and Chordia, Green, and Kottimukkalur (2018).

[7]A notable exception is the work of Birru and Figlewski (2010) who suggest prices under react to FOMC announcement news.

announcements as a measure of monetary policy news and show that the news is reflected into prices almost immediately at the announcement. This finding supports the latest studies documenting close to immediate price discovery following macroeconomic news (e.g., Hu, Pan, and Wang, 2017). Consistent with Birru and Figlewski (2010), we find evidence of price under reaction unrelated to the surprise, but also price reversal due to price pressure.

1. Data and Stylized Facts

Our analysis relies on intraday quotes and trades data for two very liquid proxies of the equity market, the S&P 500 Futures (EMini) and the SPDR S&P 500 exchange-traded fund (SPY), around days of FOMC announcements. We begin by describing the FOMC and the sample of announcements, followed by a description of the equity data used in this study.

1.1. FOMC announcements

The FOMC is the monetary policy-making body of the U.S. Federal Reserve System. To meet its dual mandate of maintaining stable prices and maximum employment, the FOMC oversees the nation's open market operations, i.e., purchases and sales of U.S. Treasury and Federal Agency Securities, which affect the cost and availability of money and credit in the economy. The committee holds eight regular meeting per year to decide on monetary policy. While it was left to market participants to infer decisions from these open market operations before 1994, policy decisions are now announced in a press statement. Importantly, announcement dates are known at least six months in advance, and therefore independent of (short-term) economic conditions, and are followed closely by most market participants.[8]

[8]The FOMC can meet and make announcements outside this schedule, typically in response to drastic deterioration in the economy. We do not study these announcements.

1.1.1. Sample description

To be able to match FOMC announcements with intraday stock market data used in this study, our sample starts in September 1997 and ends in December 2017, covering a total of 163 FOMC announcements. We exclude one FOMC announcement for our analysis, the FOMC of August 9, 2011. This announcement occurred at the height of the Eurozone debt crisis, three days following a downgrade of the U.S. credit rating by Standard and Poors, and it was announced by the Fed that the rates were to remain "exceptionally low". Financial markets were volatile the week before and the week of the FOMC announcement.

We conduct our analysis on the full sample of FOMC announcements as well as in three sub-samples, specifically, the "early", "middle", and "later" sample period. The date range for the three sub-samples are September 1997 to May 2004, June 2004 to March 2011, and April 2011 to December 2017, for a total of 54, 55, and 53 FOMC events.

Table IA.I in the Internet Appendix presents the FOMC announcement dates and scheduled times of the press releases. It also breaks observations by early, middle, and later sample, and indicates whether the announcements were accompanied by a scheduled press conference.

1.1.2. Time-stamps for FOMC announcements

Since our analysis relies on high-frequency intraday data, we verify if the FOMC announcement coincides with its scheduled time. To ensure the correct time, we rely on two sources. First, we obtain millisecond-precision timestamps for the June 2004 to December 2016 period from Thomson Reuters Tick History (TRTH) provided by the Securities Industry Research Centre of Asia-Pacific (SIRCA). Second, we backfill the early part of the sample using minute-precision timestamps provided in the Internet Appendix of Bernile, Hu, and Tang (2016). Figure A1 shows FOMC announcement release time delays, defined as the time difference between the actual timestamp of the news release and the scheduled time. We

observe significant variation in the release delay before 2013, when a statement released four minutes before or after the scheduled time was not unusual. In 2013, the timeliness of releases improved dramatically. This coincides with the harmonization of announcement times for meetings with and without scheduled press conferences by the Chairperson of the Federal Reserve, and apparently reflects a general effort of the FOMC to ensure a standardized and precise communication schedule.

1.1.3. FOMC announcement contents

Because the objective of our research is to examine whether trading reflects learning about the news content of FOMC announcements, it is important to understand if and how the information contained in press releases has changed over time. Figure A2 in the Appendix shows the number of words and sentences in FOMC statements[9] from 1994 to 2018. While there is some meeting-to-meeting variation, the length of statements has approximately tripled between 2008 and 2013. Reflecting the desire of Chairman Bernanke for greater transparency, FOMC statements not only have become longer but now provide a more detailed discussion of the economic outlook.

The press statements are not the only information provided by the FOMC. Other significant changes in the amount of information released around FOMC statements include (1) the disclosure of the voting decisions by the committee members in FOMC statements since March 2002; (2) the release of the Summary of Economic Projections for four out of eight FOMC announcements since October 2007; (3) the introduction of press conferences by the Chairperson of the Federal Reserve following the statement release for four out of eight FOMC announcements since April 2011; (4) and since 2015, the release of implementation notes at the same time of press statements that specify the exact open market operations used to achieve monetary policy goals.

While all these measures clearly increase the amount of information released at any given

[9]We exclude stop-words and the paragraphs on the voting decisions of each member.

time, Boguth, Grégoire, and Martineau (2019) show that opting to provide the Summary of Economic Projections and holding press conferences on only four of the eight annual meetings has an unintended, potentially more important, effect on equity prices and investor attention to monetary policy. FOMC announcements with scheduled press conferences are accompanied with news deemed more relevant to market participants as evidenced by the significant difference in the resolution of uncertainty, risk premium, and changes in eurodollar rates. Differentiating between announcements with and without scheduled press conferences is important to our main empirical analysis.

1.2. Equity market data, trading volume, and realized volatility

We proxy for the equity market by the S&P 500 index, and analyze the two most liquid financial products linked to the index: the E-mini S&P 500 Futures (EMini) and the SPDR S&P 500 ETF (SPY).[10] Intraday quotes and trades data are provided by TRTH, and timestamped at a precision of seconds for EMinis and milliseconds for SPY. To better understand the implications of price pressure on the efficiency of prices following FOMC announcements, we also rely on data from Nasdaq ITCH, which contains accurately signed buyer- and seller-initiated orders.

To provide a first indication of the importance of FOMC announcements for the equity market, Figure 1 shows the trading volume and realized volatility (sum of 1-second midquote return squared) per minute in EMinis from 60 minutes before to 90 minutes after FOMC announcements. Panels A to C present the trade volume and realized volatility for different sub-samples. In all Panels, the green dotted line shows the typical trading volume (realized volatility) on the previous ten trading days.

As documented in Fleming and Remolona (1999) and Rosa (2016) for treasury bonds

[10]Hasbrouck (2003) finds that most of the price discovery occurs in the E-Mini market. In a more recent sample, Budish, Cramton, and Shim (2015) show that EMini and SPY prices comove almost perfectly because of high-frequency arbitrageurs.

and E-minis, respectively, trade volume prior to the announcement is slightly lower than on benchmark days, it surges at the announcement to approximately five times the benchmark volume, and then gradually returns to its benchmark level about one hour after the announcement. In contrast to these studies, we show that trade volume around FOMC announcements has increased over time. At the announcement, the average trade volume was approximately 2,000 contracts between 1997 to 2004 before reaching average heights varying from 10,000 to 20,000. The total trading volume in the window from one minute before to ten minutes after the announcement is on average 2.8 times the benchmark from September 1997 to March 2004, 5.2 times the benchmark from June 2004 to March 2011 and 4.9 times the benchmark from April 2011 to December 2017. Realized volatility jumps at the announcement and gradually decays at a similar rate as trade volume.

2. Price Discovery

The key question we study in this paper is how the new information from FOMC announcements is incorporated into prices, and whether the large trading volume following these announcements aids or hinders this price discovery process. The main challenge in the analysis of price discovery is that the "fair" price is unobservable. We now specify the information environment underlying the empirical tests and present our main results on the price formation process following FOMC announcements.

2.1. The theoretical framework and hypotheses

Consider four time periods surrounding the FOMC announcements, where $t = 0$ corresponds to a time just prior to the event. There is one single information flow I at the announcement ($t = 1$). However, liquidity providers can only process a subset I_1 of the information immediately, and therefore only I_1 enters prices at this time. Other market participants can potentially process the entire information I. The post-event period $t = 2$ is characterized by

large observable trading volume. By the terminal time $t = T$, the information I has been processed by all market participants, including liquidity providers, and is fully reflected in prices; trading volume has returned to normal levels.

In this setting, the log price p_T of an asset at time T is equal to its "fair" value, or equilibrium value, and we label it future indicative price. Assuming the time period considered is sufficiently short that discount rates can be ignored, the observed prices at times 0 and 1 are the unconditional and I_1-conditional expectations of the future indicative price, respectively:

$$p_0 = \mathbb{E}\left(p_T\right) \qquad\qquad p_1 = \mathbb{E}\left(p_T \,|I_1\right) \tag{1}$$

Empirically, the interesting question is what information is reflected in the observed price at time $t = 2$. There are three broad possibilities: first, observed prices could be unaffected by the order flow and, since no new information is revealed, $p_2 = p_1$. We call this the volume irrelevance hypothesis, and it is supported by the evidence that the equity market reacts quickly and efficiently to new public information (Hu, Pan, and Wang, 2017, Chordia, Green, and Kottimukkalur, 2018, Grégoire and Martineau, 2018), and that the assets we analyze are among the most liquid financial instruments available (Hasbrouck, 2003).

Second, the order flow during this time period could be informative about the future indicative price, and we would observe a price p_2 that reflects some of the information contained in $I - I_1$. In this case, prices move towards the efficient level, and the return from period 1 to period 2 is positively correlated with the return from period 1 to period T, $\mathrm{Corr}\left(p_2 - p_1, p_T - p_1\right) > 0$. As long as prices fully reflect the processed information at time $t = 2$, non-overlapping returns will be uncorrelated: $\mathrm{Corr}\left(p_2 - p_1, p_T - p_2\right) = 0$. We label this the learning hypothesis, and broad empirical evidence for learning in a similar context is provided, among others, in Biais, Hillion, and Spatt (1999). This learning hypothesis is consistent with several theoretical microstructure frameworks where the agents responsible to set prices, i.e., liquidity providers, learn from order flow (e.g. Glosten and Milgrom, 1985).

Lastly, the order flow could introduce noise into the price process: p_2 would differ from

p_1, but in a way unrelated to information $I - I_1$. In this case, $\text{Corr}\left(p_2 - p_1, p_T - p_1\right) = 0$, and a direct implication of this hypothesis is that the noise introduced by trading must revert, i.e., $\text{Corr}\left(p_2 - p_1, p_T - p_2\right) < 0$. We label this the noise hypothesis, as the future indicative price at time T does not reflect any of the price impact from the order flow, and there is abundant evidence that order imbalances can drive prices of illiquid assets away from their fundamentals (e.g., Hendershott and Menkveld, 2014).

2.2. Empirical method

To examine these hypotheses, we rely on unbiasedness regressions similar to Biais, Hillion, and Spatt (1999), who use such methodology to examine the role of order flow in the pre-opening auctions to price efficiency in the French equity market. In contrast to a vast number of studies examining price discovery following macroeconomic news (e.g., Andersen, Bollerslev, Diebold, and Vega, 2003, Hu, Pan, and Wang, 2017), this method allows us to examine price formation without relying on a pre-specified measure of unexpected news. In the context of FOMC announcements, studies commonly use the Fed fund surprise as in Kuttner (2001) to evaluate the impact of monetary policy news shock on asset prices. While surprises in the Fed funds rate play an important role (Kuttner, 2001), the information revealed is multi-dimensional (e.g., Gürkaynak, Sack, and Swanson, 2005b) and the same surprise in the Fed funds rate can be interpreted differently by markets (Laarits, 2018). Moreover, Nakamura and Steinsson (2017) also shows that the Federal Reserve has made greater use of forward guidance in their press releases, which has large impacts on equity prices, but its surprises are difficult to quantify empirically. The disadvantage of this approach is that it only allows us to evaluate prices relative to unobservable information flow.

Formally, for given $0 < t < T$, we regress total returns surrounding announcement i onto the partial announcement return ending at t:

$$p_{i,T} - p_{i,0} = \alpha_t + \beta_t \left(p_{i,t} - p_{i,0}\right) + \varepsilon_{it}. \tag{2}$$

Here, $p_{i,0}$ is the log price of the frontmost EMini futures 30 minutes prior to FOMC announcements i, and $p_{i,T}$ is the closing settlement price on the next trading day at 4:15 p.m. Our chosen window is longer than typical announcement returns considered in the literature. Extending the window to include the next trading day introduces noise in our analysis as our returns contain information unrelated to the FOMC announcements. However, it is necessitated by our aim to understand the role of the increased trading volume in the hours after the events in the price formation process.

We estimate one unbiasedness regression for each minute t across FOMC announcements i, starting 10 minutes before the FOMC announcement ($t = 10$) until one minute before settlement on the following trading day. At each point in time t, both the β_t and the corresponding regression R^2, hereafter denoted with a t-subscript ${R^2}_t$, are informative about the price formation process.

Under the null hypothesis of perfectly efficient prices, the regression beta should always be one, indicating that prices follow a martingale. In our setting, as there is likely very little information revealed prior to the announcement, we expect betas to be very imprecisely measured for small t. At the time of the FOMC announcement, as the partial announcement return on the right-hand side of the regression now contains a large part of the information of the total announcement return on the left-hand side, we expect the precision in the estimation of betas to increase. If prices are not perfectly efficient, beta can help to identify if prices systematically over or underreact to the announcement information. A beta greater than one following the announcement indicates an initial underreaction to the news, and a beta less than one an overreaction. If beta is not equal to one, prices can still be informative, but not efficient.

The regression R^2 measures how much of the total announcement returns variation across events is reflected in the partial announcement returns. In other words, the R^2 reflects the informational content or the price informativeness. As a function of t, it is clear that ${R^2}_t$

will start at zero and approach one as t approaches T. The exact pattern depends on assumptions on the timing and importance of information. With constant information flow and one important announcement, we expect a constant linear increase combined with an upward jump at the time of the announcement.

We illustrate these patterns in Figure A3 of the appendix for the case of constant information flow (red dashed line) and constant information flow with a significant announcement (blue solid line). A detailed description of the simulation is provided in Section A.

The behavior of ${R^2}_t$ is revealing about the price informativeness. The benchmark depends on the underlying dynamics of information flow and processing ability. With constant information flow other than the announcement, both the volume irrelevance and the learning hypothesis predict that ${R^2}_t$ continues to increase after the announcements, possibly with a higher slope than prior to reflect that liquidity providers might process the information or learn from the order flow. Distinguishing between these hypotheses would rely on whether the fastest increases in price informativeness coincide with the largest trading volume.

In contrast, the noise hypothesis predicts that the large volume following the announcements drives prices away from their efficient levels, and therefore makes them less informative. Under this view, ${R^2}_t$ would increase at a rate slower than the information flow, or even decrease, when the volume is largest.

2.3. Unbiasedness Regression Evidence

We begin our empirical analysis with the estimates from the unbiasedness regressions on the full sample of FOMC announcements between 1997 and 2017. Panel A of Figure 2 plots β_t and the ${R^2}_t$ for t ranging from 10 minutes prior to the announcement to 1,560 minutes (26 hours) after the announcement, which is approximately the closing settlement of the following trading day.[11] Beta is close to one throughout, but the ${R^2}_t$ paint an interesting

[11] We continue to assume that the efficient price without information is given 30 minutes prior to the announcement; the 10 minute cutoff is only for illustration purposes. As shown in Table IA.I in the Internet

picture about price informativeness.

First, at closing settlement of the event day at approximately minute 125, the R^2 is around 0.25. While at this time, the right-hand side of the regression only captures about 3/27 of our event window, or about 3/9.5 of equity trading hours, this is nevertheless surprising since we would expect the FOMC announcement to reflect the majority of the information revealed in that time. Second, the overnight period, approximately minutes 125 to 1,175) contributes little to making prices more informative, consistent with a slowed information flow (e.g., low trade volume and quoting activity) during those hours (Barclay and Hendershott, 2003). Lastly, about half of the price informativeness is gained during the last 360 minutes of equity trading hours on the day following the announcement.

To get a better understanding of the dynamics of price efficiency and informativeness, and its relation to the large trading volume following the announcements, Panel B zooms in and shows the same information for t from 10 minutes prior to 125 minutes after the announcement, approximately the closing settlement of the announcement day. β_t are close to zero prior to the announcements, but with very large confidence bounds. At the event, beta jumps to around 1.5, before dropping back to 1 after about five minutes. The underreaction is statistically weak and short-lived.

Similarly, ${R^2}_t$ are zero initially and jump to about 0.15 at the announcement. This effect seems rather small given the large impact FOMC announcements have on equity prices (Bernanke and Kuttner, 2005). More interestingly, the period with the highest trading volume, the first hour after the event, is not associated with any further increases in price informativeness, as ${R^2}_t$ remains flat at approximately 0.15. It is only after 60 minutes that price informativeness starts increasing slightly to about 0.3 by the closing settlement.

Overall, our full-sample evidence of a small increase in ${R^2}_t$ at announcement, therefore,

Appendix announcements were made at 2:15 p.m. for most of our sample; several announcements were at 12:30 p.m., and since 03/2013, the statement is released at 2:00 p.m. Hence, 1560 minutes correspond to the difference between an announcement at 2:15 p.m. and the settlement time on the next trading day.

suggests that either FOMC announcements only reveal little price-relevant information relative to the following day, or that the equity market reacts to this information only with a significant delay of several hours. The large trading volume following the announcement does not aid price discovery in the first hours following the announcement, and seems to lead to less informative prices.

2.4. Subsample analysis

We now repeat the analysis on three different subsamples distinguished by time, and on two subsamples separated by an ex-ante measure of information flow and investor attention. Over the approximately 20 years of our sample markets have changed substantially: trading volume has increased drastically, in part due to the advent of high-frequency traders that exploit the improved information processing ability. Market liquidity and trade volume have increased, and price efficiency is frequently believed to have improved (Chordia, Roll, and Subrahmanyam, 2011). At the same time, the excess volume after announcements has also increased, from being less than three times benchmark volume to about five times benchmark. Potential learning or noise effects from order flow should, therefore, be more pronounced in the latter two subsamples.

Results for the early period from September 1997 to May 2004 are shown in Panel A of Figure 3. Overall, the evidence is comparable to the one from the full sample in Figure 2: the effect of the announcement is small as evidenced by the increase in ${R^2}_t$ to less than 0.10 at the announcement, but there is no evidence for systematic over or underreaction to the news as evidenced by β_t close to one. Price informativeness increases slowly in the two hours following the announcement, but returns during equity market hours on the following day contribute about half of the total information in prices.

For announcements between June 2005 to March 2011, Panel B of Figure 3 shows that ${R^2}_t$ jump to about 20% at the announcement. While it is tempting to conclude that prices are

more informative, this subsample includes the financial crises and could be characterized by FOMC announcements with large information content. Interestingly, prices do not become any more informative in the remaining two hours of the trading day.[12] On the contrary, ${R^2}_t$ declines after the initial reaction. Similar to before, equity trading hours on the following day contribute around 60% to the total return in this period. The evidence suggests that liquidity providers correctly interpret the information, and maybe the initial order flow, at the time of the announcement and update quotes accordingly. They might underreact slightly as β_t is above one, but statistically insignificant. The order flow over the next two hours, on the other hand, only reflects rebalancing trades that do not contribute to an increase in price informativeness.

The evidence from the late sample, April 2011 to December 2017, in Panel C of Figure 3 is somewhat different. We observe substantial price undereaction with the β_t above two, and statistically different from one, for about 15 minutes after the announcement, then converging back and reaching one about 50 minutes post announcement. FOMC announcements during this subsample seem more impactful, as the immediate market reaction explains more than 30% of the total announcement return. Similarly to before, ${R^2}_t$ decreases for about one hour immediately after the announcement, consistent with the noise hypothesis.

This evidence across subsamples is consistent with the hypothesis that more trading, even after controlling for the general increase in volume over time, is associated with a decline in price informativeness. The order flow induces noise in prices that overshadows the quickly incorporated information. The noise persists for at least 60 minutes after the announcement.

The latter sample allows us to dig a little deeper to better understand the price discovery process. Boguth, Grégoire, and Martineau (2019) show that FOMC announcements followed by press conferences tend to command more investor attention ex-ante and convey more

[12]Repeating this analysis by excluding FOMC announcements at the height of the financial crisis, as in Kroencke, Schmeling, and Schrimpf (2018), presents similar findings. We present the results in Figure IA.1 of the Internet Appendix.

information than those without.

We perform this analysis in Figures 4 and 5 for announcements with and without scheduled press conferences, respectively, and a striking difference emerges. When there is a press conference, the return in the minutes surrounding the announcement explains more than 0.4 of the variation in our total return over the approximately 27-hour window. Price informativeness then declines drastically, with ${R^2}_t$ 60 minutes after the announcement around 0.15. Interestingly, for 20 out of the 28 observations in this sample, the press conferences start 30 minutes after the announcement and last approximately until minute 90. Price informativeness declines even though information is provided during the press conference.[13] By the end of the trading day, prices are approximately as informative as immediately after the announcement.

When there is no scheduled press conference, we find no evidence that relevant information is impounded in futures prices at the announcement. This is consistent with two findings in Boguth, Grégoire, and Martineau (2019): investors pay less attention to the announcement, or the announcement does not convey any new information. Interestingly, about 60 minutes after the announcement, ${R^2}_t$ starts increasing rapidly, and reaches about 0.6 by closing settlement. This is much higher than we might expect under a constant information flow hypothesis, since closing settlement occurs approximately 2.5 hours into our 26.5 hour window. This suggests that information is revealed even at those announcements without press conferences, but it is either initially ignored by market participants or takes significant time to interpret.

2.5. Markets reversals and predictability

The decline in ${R^2}_t$ following FOMC announcements provides strong evidence that prices one hour after the announcements are more noisy than those immediate after the news is

[13] In the remaining observations, press conferences start 105 minutes after the announcement.

released. While interpreting the economic magnitude of the noise effect is difficult from ${R^2}_t$ alone, consistent with the theoretical framework above we expect noise to revert, allowing us to estimate the magnitude of price distortions.

To examine the potential presence of price reversals and their magnitudes, we estimate the following regression for FOMC announcements with press conferences:

$$p_{i,T} - p_{i,t} = \alpha_t + \beta_t(p_{i,t} - p_{i,t_1}) + \varepsilon_{i,t} \qquad t_1 < t < T, \tag{3}$$

where $p_{i,T} - p_{i,t}$ is the E-Mini log return from time t until the next day settlement price, and $p_{i,t} - p_{i,t_1}$ is the return from 10 minutes following the announcement (t_1) to time t. We begin measuring the returns 10 minutes after the announcement to ensure liquidity providers have the opportunity to process the information in the announcement and in the early, potentially informative, trades. This choice of starting time coincides with the time when price informativeness starts to decrease.[14] We present the estimated β_t and ${R^2}_t$ in Figure 6.

Panel A shows return reversals after announcements, as indicated by the negative coefficient estimates. Predictability is strongest, as measured by the highest ${R^2}_t$ around 50 minutes after the announcement ($t = 50$), consistent with the prior evidence that price informativeness is lowest at approximately that time. The coefficient exceeds -2, indicating that the temporary mispricing is twice as large than returns measured from $t = 10$ to $t = 50$ minutes.

The mean absolute returns during this period in our sample is 28 basis points. Therefore, our model predicts a reversal of over 56 basis points between between 50 minutes after the announcement and the end of the next trading day. The ${R^2}_t$ at $t = 50$ indicates that 40% of the variation in future returns is related to temporary deviation from efficient pricing.

To ensure that we are not capturing only very high-frequency reversal, which can be

[14]We have considered alternative starting times of 5 minutes and 15 minutes post announcement, and our main findings are robust to these variations.

expected in times of high realized volatility, we now estimate predictability of returns on the following trading day:

$$p_{i,T} - p_{i,t_2} = \alpha_t + \beta_t(p_{i,t} - p_{i,t_1}) + \varepsilon_{i,t} \qquad t_1 < t < t_2 < T, \tag{4}$$

where $p_{i,T} - p_{i,t_2}$ the E-mini log return between settlements on the announcement day and the following day. t_1 remains fixed at 10 minutes post announcement. The results presented in Panel B of Figure 6 closely mirror the previous results. Even though the magnitude of the estimated coefficients is slightly smaller, most of the reversal occurs on the next day and that the mispricing survives beyond the initial market closing auction and the futures market settlement period.

Another way of looking at mispricing is to see whether there is evidence of continuation during the time mispricing corrects. We test this insight by estimating the following equation:

$$p_{i,T} - p_{i,t_2} = \alpha_t + \beta_t(p_{i,t_2} - p_{i,t}) + \varepsilon_{i,t} \qquad 0 < t < t_2, \tag{5}$$

where again t_2 and T correspond to settlements on the announcement day and the following day. The results presented in Panel C show that the coefficient estimates are consistently positive, indicating persistence, and statistically significant between about 50 minutes and 110 minutes. In other words, returns towards the end of the announcement day returns are positively related to returns on the following day.

Our results so far show that there is significant predictability due to low price informativeness in E-Mini futures following FOMC announcements. We argue that the common systematic news leads to correlated order flow in the underlying stocks that aggregates to the index, and that the price behavior of the E-mini reflects the underlying index. However, while we consider the magnitude of predictability is large given that E-Mini futures are the most liquid instruments for trading in the S&P 500 index, it is qualitatively not surprising that order flow can temporarily impact prices of one individual asset. In other words, the E-mini futures might be a bad proxy for the market at the times we analyze.

We perform two tests to address this concern: first, we directly compare the prices of the underlying basket of securities of the E-Mini future or the SPY exchange traded fund and find no economically significant increase in premia or discounts (untabulated). Second, we repeat the analysis of Figure 6 on S&P 500 index returns computed directly from underlying stock prices. To perform this analysis, we rely on equity market closing times (4 p.m.) instead of futures settlement time (4:15 pm). Figure IA.3 in the Internet Appendix confirm that the predictability effects are not specific to E-Mini, and are present in S&P 500 index stocks.

Altogether, the increased trade volume following FOMC announcements is not associated with an increase in price informativeness. Instead, prices one hour after the announcement often are worse indicators of future prices than the ones observed immediately after the announcements. The evidence shows that in these times of large trading volume prices turn less informative, and the noise in prices reverts over the next trading day. We have shown that the price inefficiencies coincide with times of large trading volume. The next section demonstrates the causal impact of order flow to price inefficiencies.

3. Price pressure

Results presented in the previous section show that the surge in trading following FOMC announcements is not associated with better price informativeness. To the contrary, we document that price become less informative in the first hour after the announcement. This temporary mispricing leads to strong predictability. We now show that price pressure arising from order imbalances causes the mispricing.

We hypothesize that the temporary mispricing is caused by abnormal demand for liquidity where the order imbalance is too large for liquidity providers to accommodate without buying (selling) at a discount (premium) relative to future prices. While we cannot observe liquidity providers inventory positions, we have access to *signed* order flow for the SPY ETF on

the NASDAQ stock exchange to construct measures of buying and selling pressure. We implicitly assume that the observed order imbalance for SPY on NASDAQ is a reflection of the aggregate imbalance in S&P 500-linked securities.

To examine the implication of price pressure on price discovery, we focus on FOMC announcements that are more likely to release important news ex-ante to improve the power of test. Without a significant change in the conditional mean of prices due to news, it is difficult to examine the implication of price pressure on price discovery. Therefore, we limit our analysis to FOMC announcements with scheduled press conferences. Confirming this selection, Figure A4 in the Appendix shows that the absolute cumulative order imbalance following FOMC announcements with scheduled press conferences is larger and more persistent than those without press conferences.

To examine the impact of price pressure on price formation, we decompose the post-announcement returns into two parts: returns explained by order imbalance and those unrelated to order flow. The decomposition amounts to the fitted value and the residual from the following regression estimated across announcements at every two-minute intervals starting at t over a 90-minute window:

$$r_{i,t:t+2} = \alpha + \sum_{j=0}^{1} \Big(\gamma_{j,t} OI_{i,t-j} + \delta_{j,t} TV_{i,t-j} + \kappa_{j,t} TV_{i,t-j}^2 + \phi_{j,t} OI_{i,t-j} \times TV_{i,t-j} + \nu_{j,t} OI_{i,t-j} \times TV_{i,t-j}^2 \Big) + \epsilon_{i,t:t+2} \tag{6}$$

where $r_{i,t:t+2} = p_{i,t+2} - p_{i,t}$ is the two minute SPY log midquote return, and $OI_{i,t}$ is the order imbalance defined as the volume of buyer-initiated trades minus the volume of seller-initiated trades, scaled by the total trade volume $TV_{i,t}$, for announcement i. We choose this general regression specification to capture the impact of contemporaneous and lagged order imbalance and the impact of order imbalance combined with a large trade volume. The average R^2 of the two-minute regressions is 40%.

We then aggregate both (fitted) returns that are explained by order imbalances and

(residual) returns that are not explained by order imbalance over time, again starting at $t_1 = 10$ minutes after the announcement,

$$\hat{r}_{i,t} = \sum_{\tau=t_1}^{t-2} \hat{r}_{i,\tau:\tau+2} \qquad \text{and} \qquad \hat{\epsilon}_{i,t} = \sum_{\tau=t_1}^{t-2} \hat{\epsilon}_{i,\tau:\tau+2} \tag{7}$$

and estimate the modified versions of regression (3) and (4):

$$r_{i,[t,T]} = \alpha_t + \beta_t^{Fit} \hat{r}_{i,t} + \beta_t^{Res} \hat{\epsilon}_{i,t} + \varepsilon_{i,t}, \tag{8}$$

$$r_{i,[t_2,T]} = \alpha_t + \beta_t^{Fit} \hat{r}_{i,t} + \beta_t^{Res} \hat{\epsilon}_{i,t} + \varepsilon_{i,t}. \tag{9}$$

Panels A and B of Figure 7 show the results of estimating equations (8) and (9), respectively. Both panels tell the same story: only the component of returns linked to order imbalance explains the return reversals. The β_t^{Fit} coefficients for predicted returns are of similar magnitude to those in Panel A of Figure 6 and statistically significant until around the 60-minute mark. The coefficients associated with the residuals, β_t^{Res}, are not statistically significantly different from zero. The magnitude of the ${R^2}_t$ are closely similar to those reported in Panel A of Figure 6.[15] Overall, our results indicate that order imbalance largely explains returns reversals following FOMC announcements in the hour following announcements through price pressure and is responsible for affecting the level of price informativeness in prices.

4. Measuring FOMC Announcements' Impact on Equity Prices

We have shown that price pressure caused by large trading volume hinders the price formation process following FOMC announcements. One remaining question is how we should measure the impact of monetary policy news shock on equity prices given price pressure making prices

[15] In unreported results, we confirm that $\hat{\epsilon}_{i,t}$ contributes little to ${R^2}_t$.

more noisy. This question is important given the significant interest in monetary policy, and that equity responses are often used to evaluate policies.

Our analysis demonstrates an initial burst of price discovery at the time of the announcement. This appears to suggest that FOMC news that is easy to process, such as changes to the Fed fund rate and expectations about future rates, is immediately incorporated into prices. Therefore, if one aims to measure correctly the monetary policy news shock associated with changes in Fed fund rates on equity prices, a short window of a few minutes (i.e., -1 to 2) around the announcement might be the most appropriate in order to capture the effect of the news shock while avoiding the noise introduced by price pressure.

Prior literature has frequently used the difference between the announced Fed fund target rate and analysts expectations (e.g., Andersen, Bollerslev, Diebold, and Vega, 2003, Zebedee, Bentzen, Hansen, and Lunde, 2008), or the change in Federal Fund futures around the announcement (Bernanke and Kuttner, 2005, Gürkaynak, Sack, and Swanson, 2007, Piazzesi and Swanson, 2008) to examine asset price responses to FOMC announcements. However, changes in federal funds rates are often largely anticipated by markets, and unanticipated changes capture only a small fraction of the monetary policy news associated with FOMC announcements (Gürkaynak, Sack, and Swanson, 2005a).

To overcome this issue, we use changes in eurodollar rates using Eurodollar futures around FOMC announcements as a measure of announcement surprise. Eurodollar futures are the most liquid contracts traded on the Chicago Mercantile Exchange. They react strongly to FOMC announcements and have been used as measures of announcement surprises in the prior literature (e.g., Gürkaynak, Sack, and Swanson, 2005a, Gertler and Karadi, 2015, Nakamura and Steinsson, 2017, Boguth, Grégoire, and Martineau, 2019). The settlement price of these derivatives is 100 minus the three-months spot London interbank offered rate (LIBOR) at maturity, and quarterly contracts trade with up to ten years of maturity. We further estimate the expected three-month LIBOR for fixed horizons by interpolation to avoid

any potential issues due to varying maturities. We refer the reader to Boguth, Grégoire, and Martineau (2019) for more details on the interpolation procedure.

Similar to Nakamura and Steinsson (2017), we define our measure of FOMC announcement surprise, ED_i, as the first principal component of changes in Eurodollar implied LIBOR rates with maturities of 2, 4, 6, and 12 quarters from one minute before to two minutes after the FOMC announcement.

To assess the impact of announcement surprises, we estimate

$$r_{i,t:t+2} = \alpha + \beta ED_i + \gamma OI_{i,t} + e_{i,t:t+2}, \tag{10}$$

where $r_{i,t:t+2} = p_{i,t+2} - p_{i,t}$ is the two-minute log midquote return of the E-mini for announcement i starting t minutes after the announcement, and $OI_{i,t}$ is the corresponding normalized order imbalance of the SPY.[16] We include the order imbalance as price discovery might occur indirectly through the arrival of trades and not directly through the adjustment in quotes. We estimate this regression across all FOMC announcements between 2011 and 2017 for every two-minute interval in the 10-minute window following the announcement. Returns in the first interval are calculated using prices one minute before to two minutes after FOMC announcements.

Table 1 reports the results for two regression specifications of equation (10) at every two minute intervals following the announcement in Panel A and over different expanding window in Panel B. Panel A shows that at the announcement (the first two-minute interval), the announcement surprise (ED) explains 56% of the returns. Including the order imbalance (OI), the explanatory power increases by only 6%. After the first two minutes, the announcement surprise is not related to returns. Therefore, the initial price discovery occurs directly through the adjustment in quotes, consistent with the recent papers documenting similar findings following earnings announcement surprises (Grégoire and Martineau, 2018)

[16] Using SPY returns instead of the Emini gives quantitatively similar results. The results are reported in Table IA.II of the Internet Appendix.

and other macroeconomic announcements (Chordia, Green, and Kottimukkalur, 2018).

Panel B provides evidence of the consequences of using a long window around FOMC announcements to capture the impact of monetary policy news on equity prices. Expanding the window from 15 to 60 minutes can decrease substantially the explanatory power, from 26% to 2% (for the univariate model) and the estimated coefficients by 22% (from 0.022 to 0.017). Using a window of 90 minutes provides a much larger coefficient of 0.052 and an R^2 of 12%. A potential reason for this increase in explanatory power when using a 90-minute window is related to price reversal as prices become more informative again after about one hour.

We conclude that at the time of the announcement, prices are driven mainly by the public information and not incoming order flow. Nonetheless, the explanatory power of order flow imbalance remains significant following this initial burst of price discovery, which is consistent with the finding in the previous section that order flow does impact significantly returns following announcements and is associated with price pressure. These results further emphasize the importance of choosing an appropriate window size following FOMC announcements when estimating the impact of monetary policy news shock on equity prices.

5. Conclusion

The goal of the research reported in this paper is to deepen our understanding of price formation in the equity market following FOMC announcements and to assess the role of trade volume. To that end, we document that fundamental monetary policy surprises contained in FOMC statements incorporate into equity prices rapidly, within two minutes following the statement release. Following the initial burst in price discovery, sizeable liquidity-taking order flow distorts price informativeness by pushing prices away from fundamentals causing temporary mispricing that is corrected hours following the announcement. Our results have direct implications on monetary policy research examining at high-frequency how eq-

uity prices respond to monetary policy news. Due to price pressure, the chosen length of the high-frequency window around FOMC announcements is not an arbitrary decision. Choosing an inappropriate window can introduce substantial noise in the estimates of price response to monetary policy news.

The significant magnitude of price pressure following FOMC announcements suggests that policymakers should find ways to reduce its impact on liquidity providers inventory risk. It might be more appropriate for FOMC announcements to happen after regular trading hours just like earnings announcements. Another possibility is for policymakers to consider trading halts at the announcement and resume trading through frequent-batch auctions to mitigate market price inefficiency. Frequent-batch auctions could minimize inventory risks faced by liquidity providers by slowing down the rate at which incoming order flow arrives, giving more flexibility to liquidity providers to properly manage their inventory.

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Figure 1. Trade Volume and Realized Volatility Around FOMC Announcements

This figure shows the 1-minute EMini futures trade volume and realized volatility 60 minutes before to 90 minutes following FOMC announcements from September 1997 to March 2004, June 2004 to March 2011, and April 2011 to December 2017 in Panels A to C, respectively. Realized volatility is calculated as the sum of 1-second midquote returns squared. The benchmark corresponds to the average trading volume and realized volatility in the 10 days prior to the FOMC announcement.

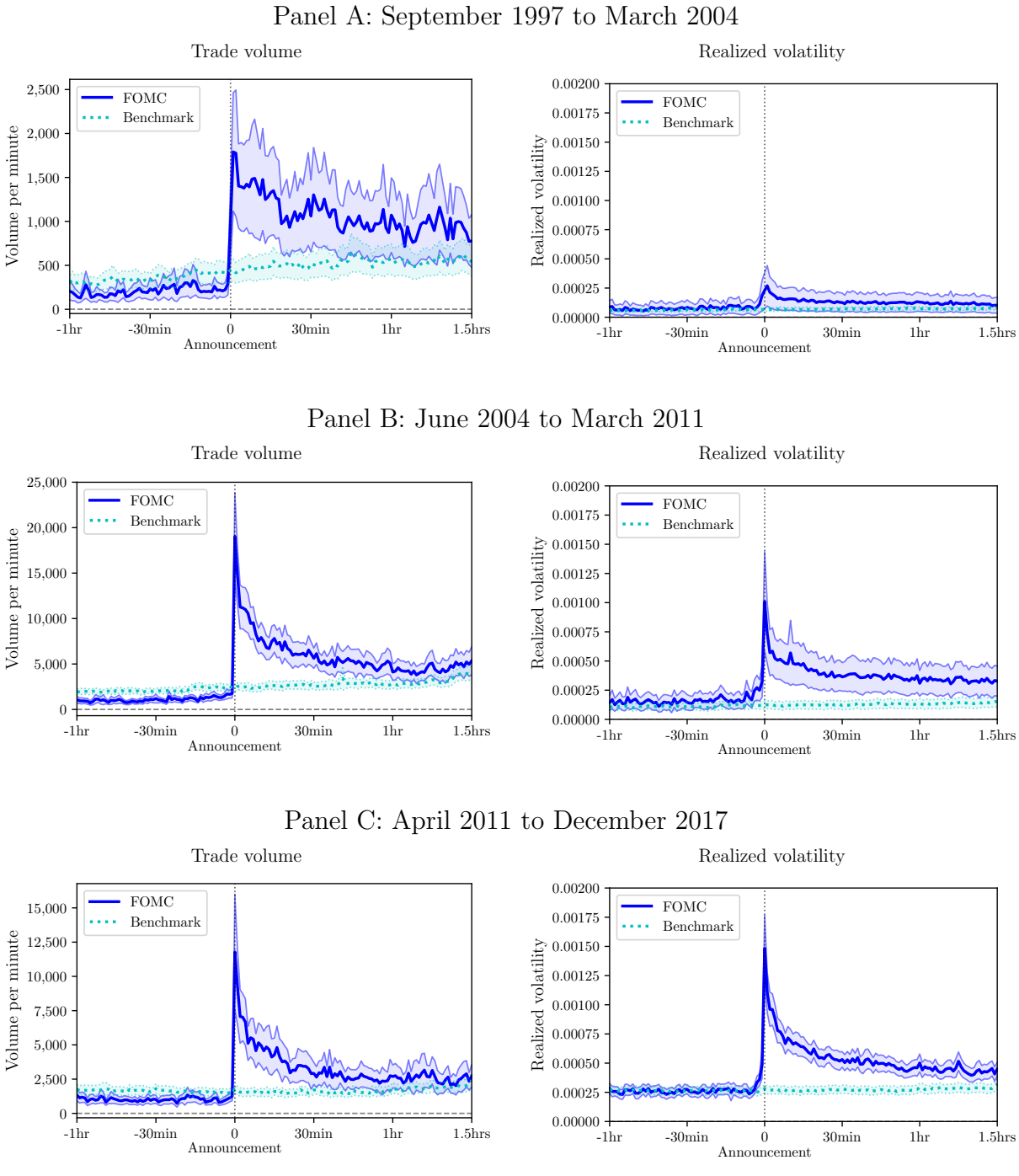


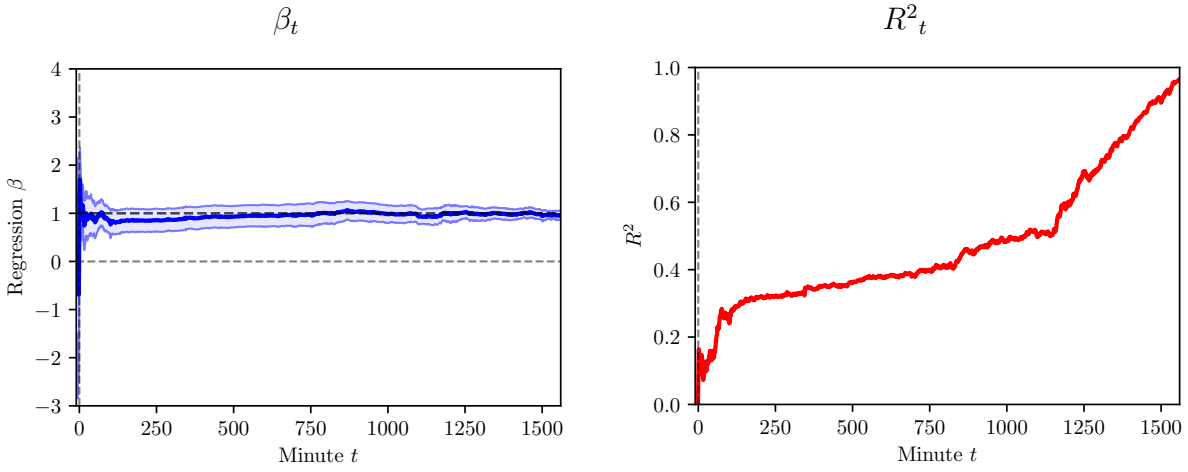
Figure 2. Price Discovery Regressions: Full Sample

This figure shows the β_t coefficient estimates and R^2s from the following regression:

$$p_{i,T} - p_{i,-30} = \alpha_t + \beta_t \left(p_{i,t} - p_{i,-30}\right) + \varepsilon_{i,t},$$

where $p_{i,t} - p_{i,-30}$ is the EMini log return from 30 minutes before the announcement to minute t around FOMC announcement i and T is the settlement price on the next trading day. Regressions are estimated independently at each time t. We present the results for $t \in [-10, 1560]$ and $t \in [-10, 120]$ in Panels A and B, respectively. The shaded areas represent pointwise 95% confidence intervals around the estimated β_t coefficients using heteroscedasticity-consistent standard errors. The sample period is from September 1997 to December 2017

Panel A. Full window, $t \in [-10, 1560]$



Panel B. Event day, $t \in [-10, 120]$

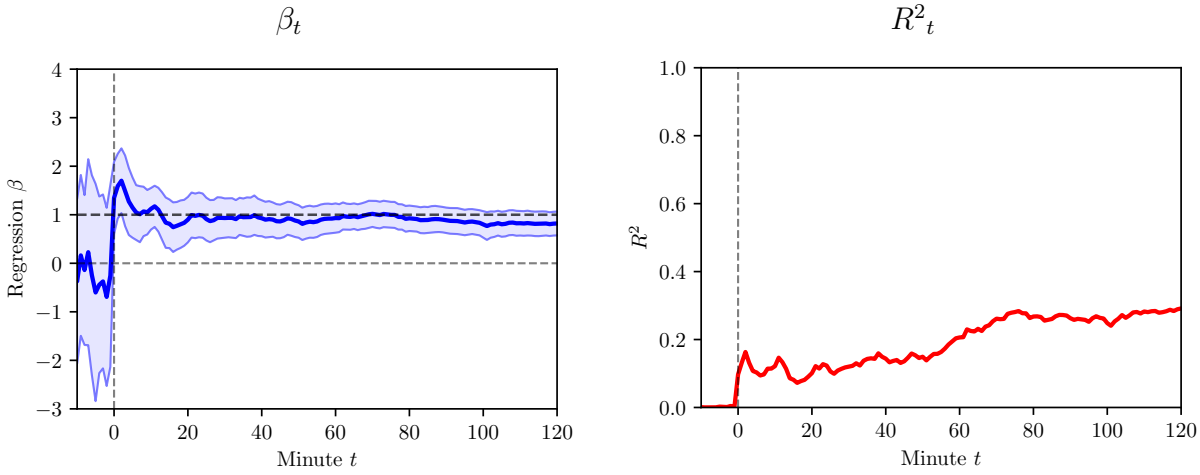


Figure 3. Price Discovery Regressions: Subsamples

This figure shows the β_t coefficient estimates and ${R^2}_t$ from the following regression:

$$p_{i,T} - p_{i,-30} = \alpha_t + \beta_t \left(p_{i,t} - p_{i,-30}\right) + \varepsilon_{i,t},$$

where $p_{i,t} - p_{i,-30}$ is the EMini log return from 30 minutes before the announcement to minute t following FOMC announcement i and T corresponds to the settlement price on the next trading day following the announcement. Regressions are estimated independently at each time t. The shaded areas represent pointwise 95% confidence intervals around the estimated β_t coefficients using heteroscedasticity-consistent standard errors. Panels A to C present the results for the sample period from September 1997 to May 2004, from June 2004 to March 2011, and from April 2011 to December 2017, respectively, for $t \in [-10, 1560]$ and for $t \in [-10, 120]$ in each panel.

Panel A. September 1997 - May 2004

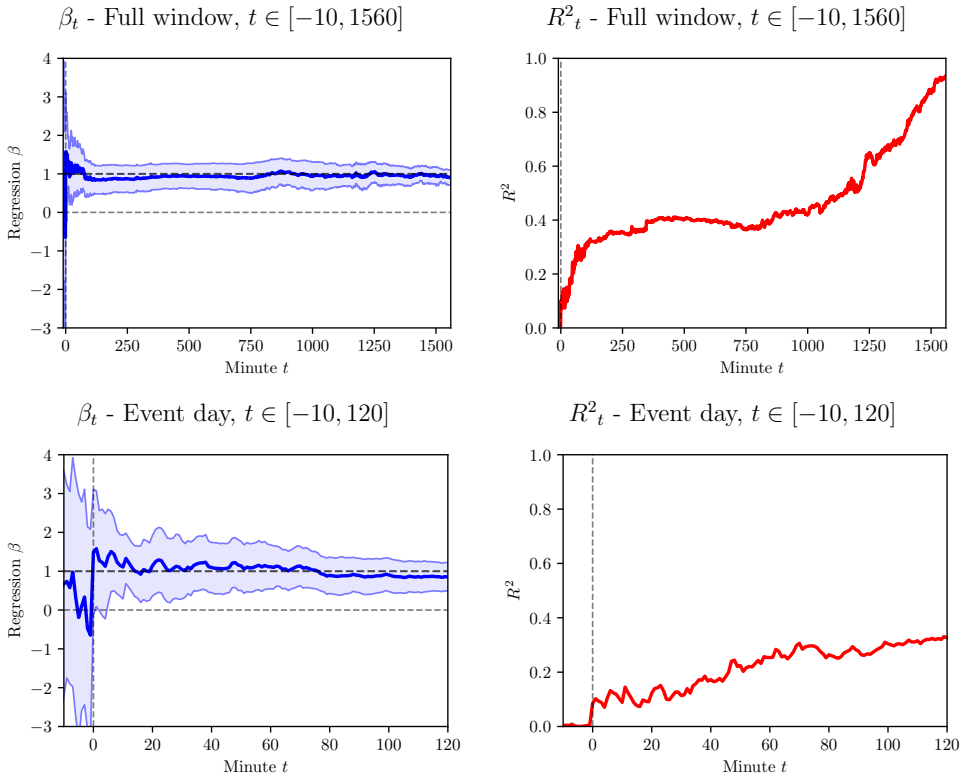
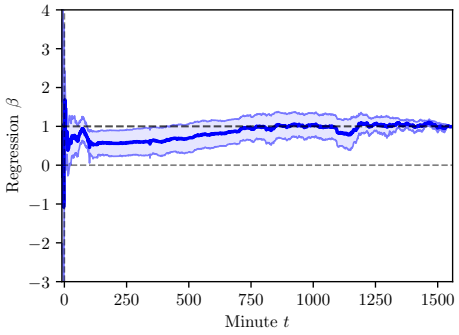


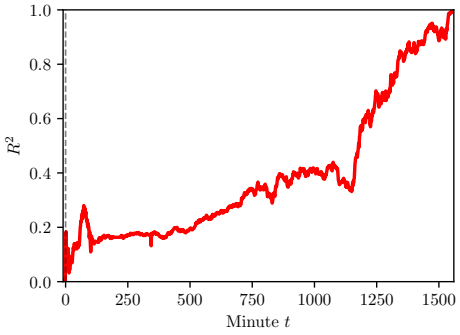
Figure 3 Continued. Price Discovery Regressions: Subsamples

Panel B: June 2004 - March 2011

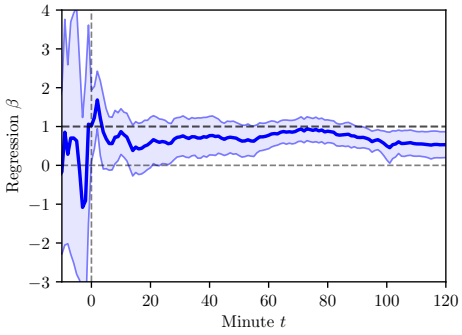
β_t - Full window, $t \in [-10, 1560]$



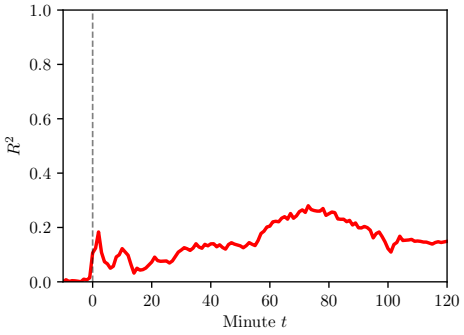
$R^2{}_t$ - Full window, $t \in [-10, 1560]$



β_t - Event day, $t \in [-10, 120]$

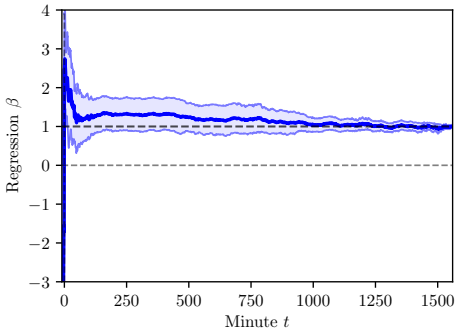


$R^2{}_t$ - Event day, $t \in [-10, 120]$

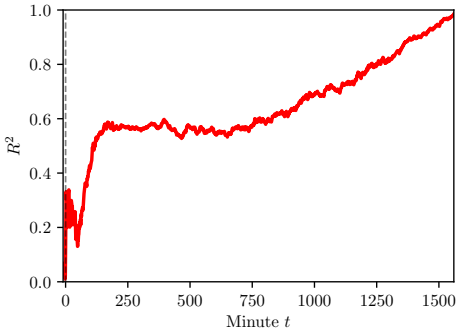


Panel C: April 2011 - December 2017

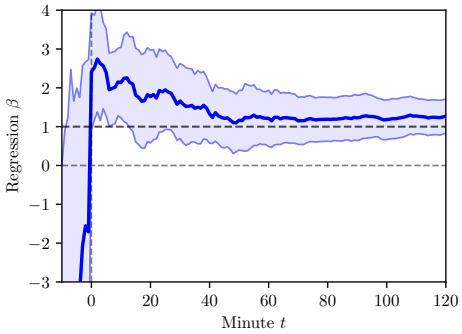
β_t - Full window, $t \in [-10, 1560]$



$R^2{}_t$ - Full window, $t \in [-10, 1560]$



β_t - Event day, $t \in [-10, 120]$



$R^2{}_t$ - Event day, $t \in [-10, 120]$

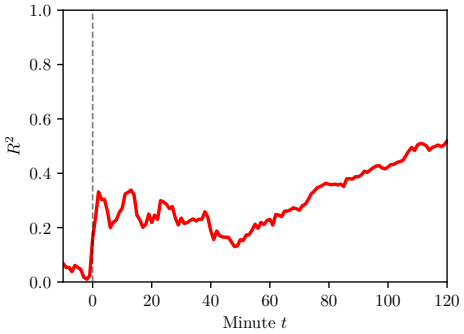


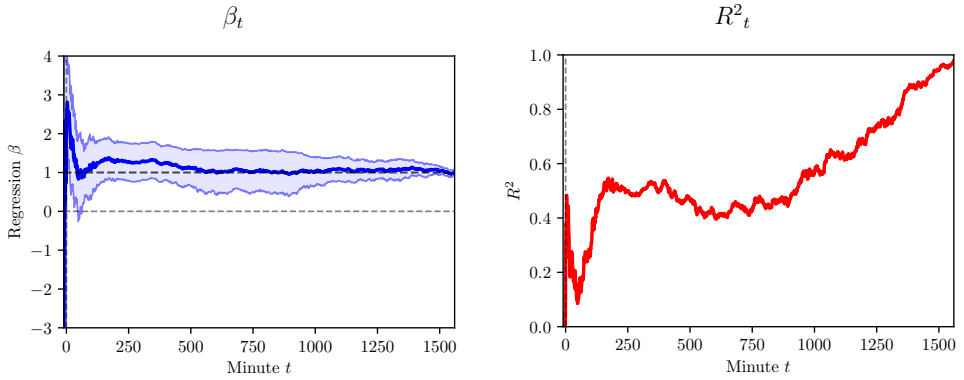
Figure 4. Price Discovery Regressions for FOMC Announcements with Press Conferences

This figure shows β_t coefficient estimates and ${R^2}_t$ from the following regression:

$$p_{i,T} - p_{i,-30} = \alpha_t + \beta_t \left(p_{i,t} - p_{i,-30}\right) + \varepsilon_{i,t},$$

where $p_{i,t} - p_{i,-30}$ is the EMini log return from 30 minutes before the announcement to time t following FOMC announcement i and T corresponds to the settlement price on the next trading day following the announcement. Regressions are estimated independently at each time t. The shaded areas represent pointwise 95% confidence intervals around the estimated β_t coefficients using heteroscedasticity-consistent standard errors. Panels A and B present the results for $t \in [-10, 1560]$ and for $t \in [-10, 120]$, respectively. The sample consists of FOMC announcements with scheduled press conferences between April 2011 and December 2017.

Panel A. Full window, $t \in [-10, 1560]$



Panel B. Event day, $t \in [-10, 120]$

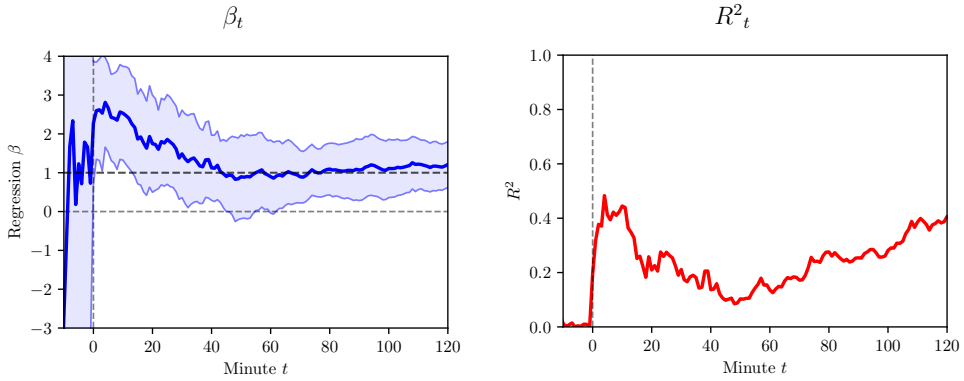


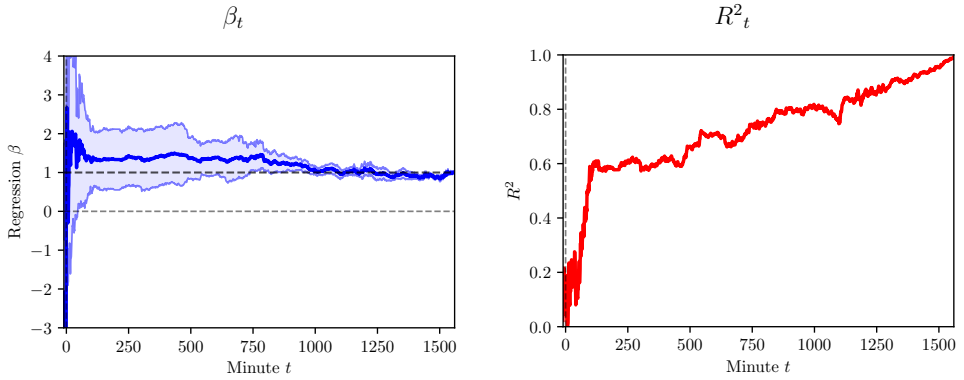
Figure 5. EMini Price Discovery Regressions for FOMC with no Press Conferences

This figure shows β_t coefficient estimates and ${R^2}_t$ from the following regression:

$$p_{i,T} - p_{i,-30} = \alpha_t + \beta_t \left(p_{i,t} - p_{i,-30}\right) + \varepsilon_{i,t}$$

where $p_{i,t} - p_{i,-30}$ is the EMini log return from 30 minutes before the announcement to time t following FOMC announcement i and T corresponds to the settlement price on the next trading day following the announcement. Regressions are estimated independently at each time t. The shaded areas represent pointwise 95% confidence intervals around the estimated β_t coefficients using heteroscedasticity-consistent standard errors. Panels A and B present the results for $t \in [-10, 1560]$ and for $t \in [-10, 120]$, respectively. The sample consists of FOMC announcements with no scheduled press conferences between April 2011 and December 2017.

Panel A. Full window, $t \in [-10, 1560]$



Panel B. Event day, $t \in [-10, 120]$

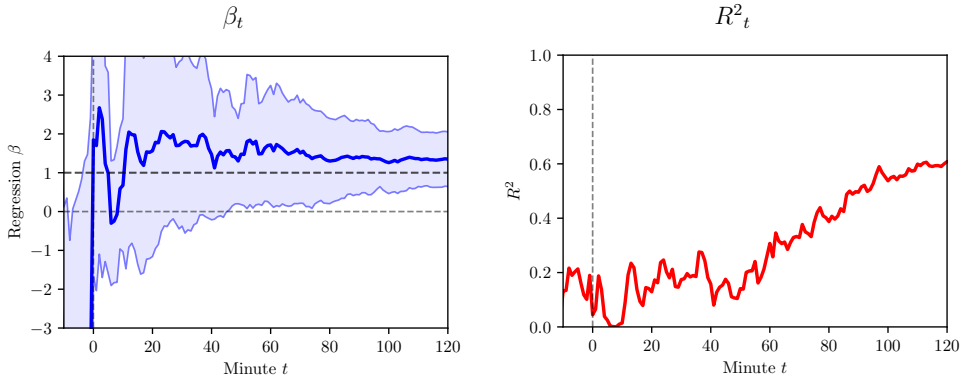


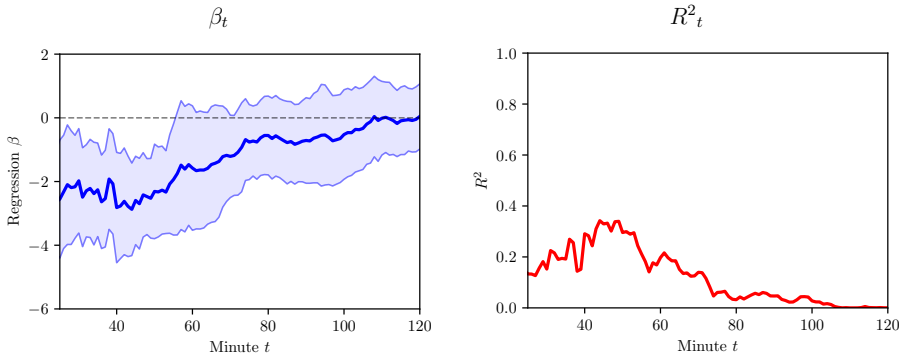
Figure 6. Price Reversals and Returns Predictability

This figure shows β_t coefficient estimates and ${R^2}_t$ from the following regressions:

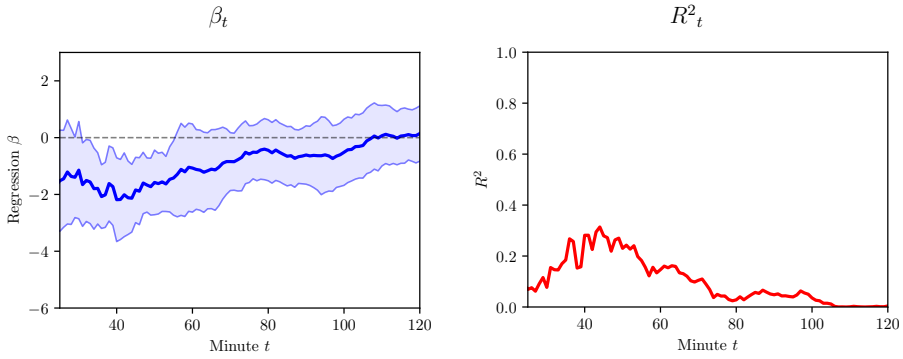
$$\begin{aligned} p_{i,T} - p_{i,t} &= \alpha_t + \beta_t(p_{i,t} - p_{i,t_1}) + \varepsilon_{i,t} && t_1 < t < T, \text{ in Panel A,} \\ p_{i,T} - p_{i,t_2} &= \alpha_t + \beta_t(p_{i,t} - p_{i,t_1}) + \varepsilon_{i,t} && t_1 < t < t_2 < T, \text{ in Panel B,} \\ p_{i,T} - p_{i,t_2} &= \alpha_t + \beta_t(p_{i,t_2} - p_{i,t}) + \varepsilon_{i,t} && 0 < t < t_2 < T, \text{ in Panel C,} \end{aligned}$$

where $p_{i,T+1} - p_{i,t}$, $p_{i,T+1} - p_{i,T}$, and $p_{i,t} - p_{i,10}$ is the Emini return from time t following FOMC announcements to the next day settlement price, is the return from the announcement day settlement price (t_2) to next day settlement price (T), and is the return from 10 minutes to time t following announcement, respectively. Regressions are estimated independently at each time t. The shaded areas represent pointwise 95% confidence intervals around the estimated β_t coefficients using heteroscedasticity-consistent standard errors. The sample consists of FOMC announcements with press conferences between April 2011 and December 2017.

Panel A. Split window



Panel B. Next day predictability



Panel C. Event day reversal

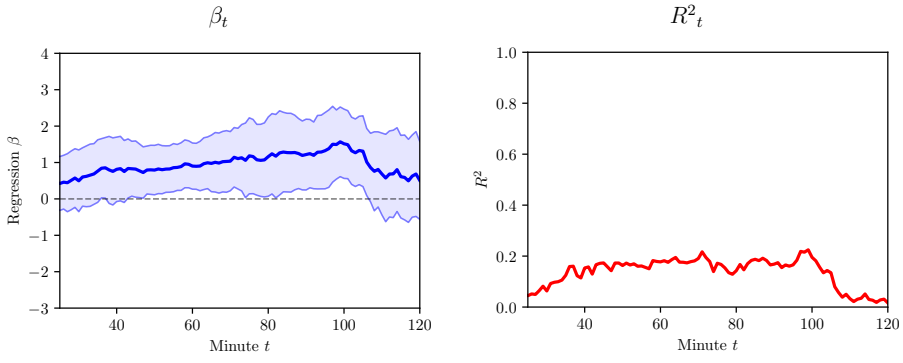


Figure 7. Order Flow and Returns Predictability

This figure shows β coefficient estimates and R^2s from the following regressions in Panel A:

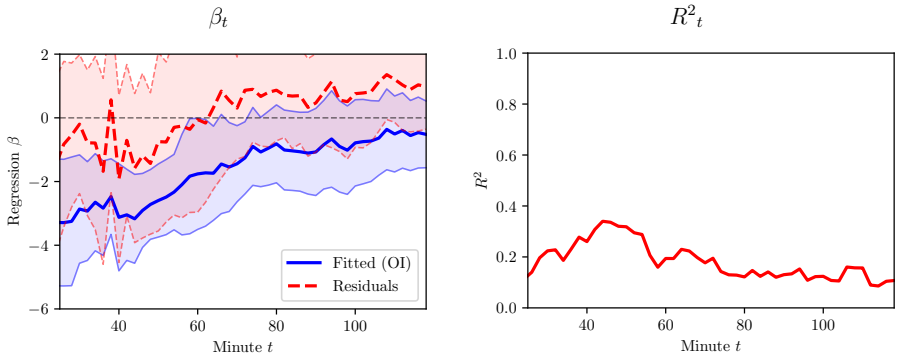
$$r_{i,[t,T]} = \alpha_t + \beta_t^{Fit}\hat{r}_{i,t} + \beta_t^{Res}\hat{\epsilon}_{i,t} + \varepsilon_{i,t},$$

and following regression in Panels B:

$$r_{i,[t_2,T]} = \alpha_t + \beta_t^{Fit}\hat{r}_{i,t} + \beta_t^{Res}\hat{\epsilon}_{i,t} + \varepsilon_{i,t},$$

where $t < t_2 < T$, $r_{i,[t,T]}$ and $r_{i,[t_2,T]}$ are the E-mini log return $p_{i,T} - p_{i,t}$ and $p_{i,T} - p_{i,t_2}$, respectively. $\hat{r}_{i,t}$ and $\hat{\epsilon}_{i,t}$ are the components of cumulative returns explained (fitted values) and unexplained by order imbalance, respectively. See the text for details on the variable construction. Regressions are estimated independently at each time t. t_2 and T correspond to settlements on the announcement day and the following day. The shaded areas represent pointwise 95% confidence intervals around the estimated β coefficients using heteroscedasticity-consistent standard errors. The sample consists of FOMC announcements with press conferences between April 2011 and December 2017.

Panel A: Split window



Panel B: Next day predictability

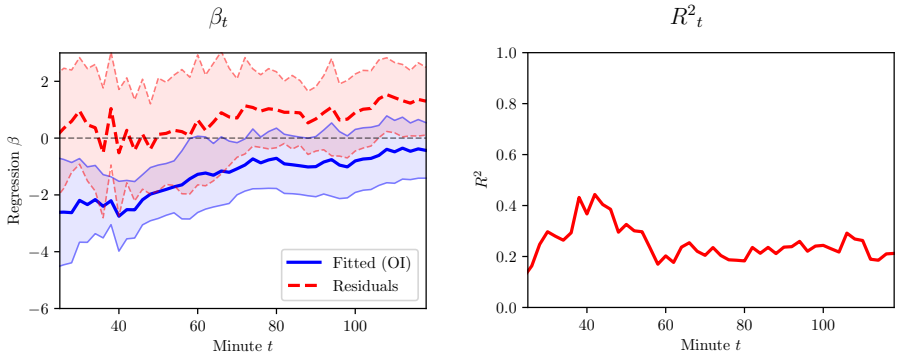


Table 1
Regression of Equity Returns on FOMC News and Order Imbalance

Panel A of this table reports coefficients from regressions of Emini returns on FOMC announcement surprises (ED) and order imbalance (OI) at every two-minute intervals following FOMC announcements, for a total of ten intervals. Returns in the first interval are calculated using prices one minute before to two minutes after FOMC announcements. Panel B reports coefficients from regressions of Emini returns on ED and order imbalance OI on an expanding window around FOMC announcements. ED correspond to the first principal component from returns of four Eurodollar contract expiring in 2, 4, 6, and 8 quarters. OI is the difference between the total number of buys and sells in trade volume divided by the total trade volume in the SPY. ** and * denote statistical significance at the 1- and 5-percent level. The standard errors are robust to heteroskedasticity. The sample period is from April 2011 to December 2017.

Panel A. Two-minute interval following FOMC announcements $(t_1 : t_2)$

	$-1:2$		$2:4$		$4:6$		$6:8$		$8:10$	
ED	0.027**	0.023**	-0.001	-0.002	-0.001	-0.001	0.001	0.001	-0.002	-0.001
	(0.004)	(0.004)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
OI		0.005**		0.006**		0.003**		0.003**		0.003**
		(0.002)		(0.002)		(0.001)		(0.001)		(0.001)
R^2	0.56	0.62	-0.02	0.17	-0.01	0.10	-0.02	0.24	-0.00	0.24
N	53	53	53	53	53	53	53	53	53	53

Panel B. Expanding window around FOMC announcements $(-1 : t_2)$

	$-1:15$		$-1:30$		$-1:45$		$-1:60$		$-1:90$	
ED	0.023**	0.018**	0.016	0.014	0.024*	0.018	0.017	0.011	0.052**	0.041**
	(0.007)	(0.006)	(0.011)	(0.010)	(0.011)	(0.009)	(0.019)	(0.016)	(0.014)	(0.013)
OI		0.017**		0.010**		0.007**		0.011**		0.006**
		(0.005)		(0.003)		(0.002)		(0.002)		(0.002)
R^2	0.26	0.37	0.02	0.21	0.09	0.25	0.02	0.31	0.12	0.25
N	53	53	53	53	53	53	53	53	53	53

Appendix

A. Simulations

To assist with the interpretation of the results presented in Section 2, we run simulations to illustrate what the β and R^2 plots would look like in an efficient market where all fundamental information is instantaneously reflected in prices.

Assume the final fundamental value of the asset, v, is revealed through a sequence of independent normally distributed shocks (continuous information flow) $\epsilon_t \sim N(0, \sigma_{flow})$ and one large normally distributed shock (news event), $\gamma_t \sim N(0, \sigma_{news})$ if $t = 0$ and $\gamma_t = 0$ otherwise:

$$v = \sum_{t=\tau}^{T} (\epsilon_t + \gamma_t) \tag{11}$$

Then in an efficient market the price p_t will reflect all the information available at time t:

$$p_t = \sum_{i=\tau}^{t} (\epsilon_i + \gamma_i)$$

We run 1000 simulations with = 27 event windows each of 300 periods ($\tau = -100$, $T = \tau 200$). We set $\sigma_{flow} = 0.001$ and repeat the exercise for two different values of σ_{news}: 0 (no news), 0.02 (news). Panel A of Figure A3 presents simulation results for the regression R^2. In an efficient market with constant information flow, the R^2 should increase linearly with time. If there is a large information event, the linear increase in R^2 is interrupted by a jump at the news release, where the magnitude of the jump depends on the magnitude of the news relative to the continuous information flow. Panel B presents simulation results for the standard errors of the regression β. By construction, the average β estimate should converge to one, but standard errors follow more interesting dynamics. In the absence of news, standard errors decrease in a quasi-linear fashion after a short initial period of rapid decrease. In the presence of news, there is a sharp decrease in the standard error the instant the news shock is incorporated into prices.

Figure A1. FOMC Release Delay

This figure shows the FOMC announcement release delay, in seconds, relative to the scheduled release time. A negative (positive) number indicates an early (late) release. The sample period is from September 1997 to December 2017.

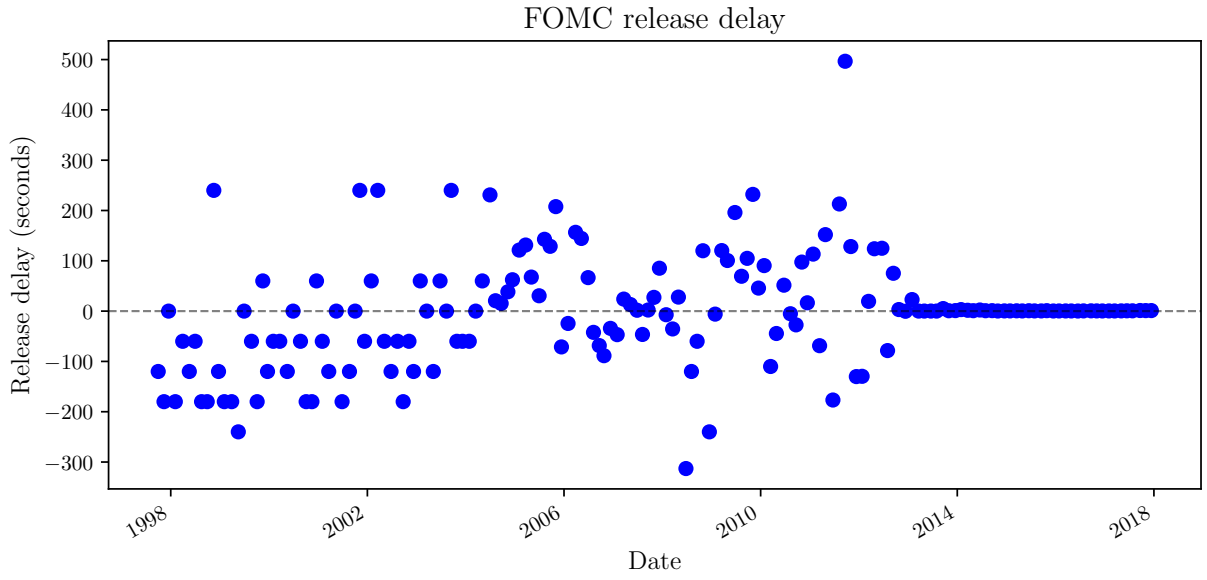


Figure A2. Information Content on FOMC Announcements

This figure shows number (N) of words and sentences in FOMC statements (excluding the paragraphs on the voting decisions of each members) from 1994 to December 2017. Several of the statements before 1999 are missing from the Federal Reserve website. We interpolate the number of words and sentences for these missing statements. The vertical lines indicate the beginning of the voting disclosure in FOMC statement (March 2002), the summary of economic projections (SEP) (October 2007), FOMC with press conferences (April 2011), and release of the implementation notes (December 2012).

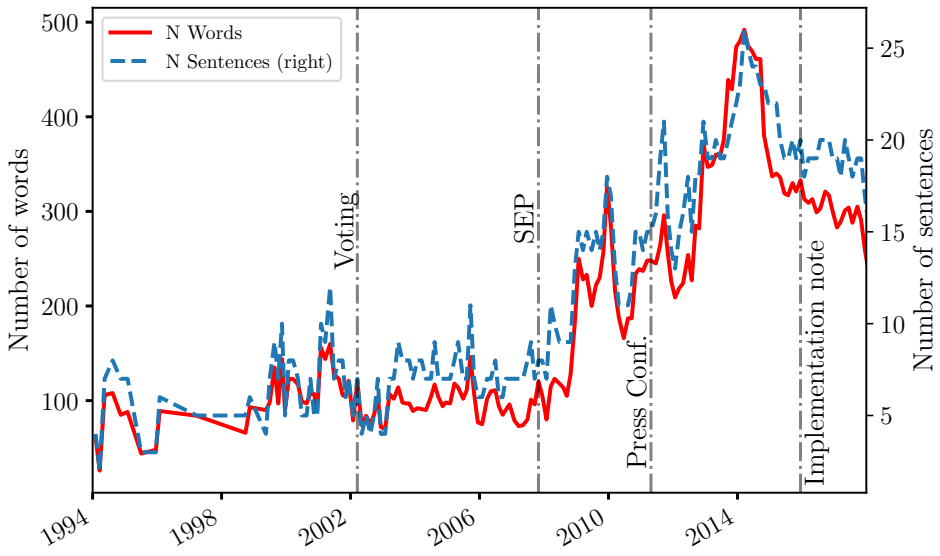


Figure A3. Price Discovery Regressions: Simulations

This figure shows the median regression R^2 (Panel A) and β standard errors (Panel B) from simulations for the sample with news (solid blue line) and no news (dashed red line). The shaded area is the region between the $2.5th$ and the $97.5th$ percentiles, encompassing 95% of sample paths. We run 1000 simulations with 27 event windows each of 300 periods ($\tau = -100$ to 200). Vertical lines indicate the announcement time. See the text for details on the simulation process and model parameters.

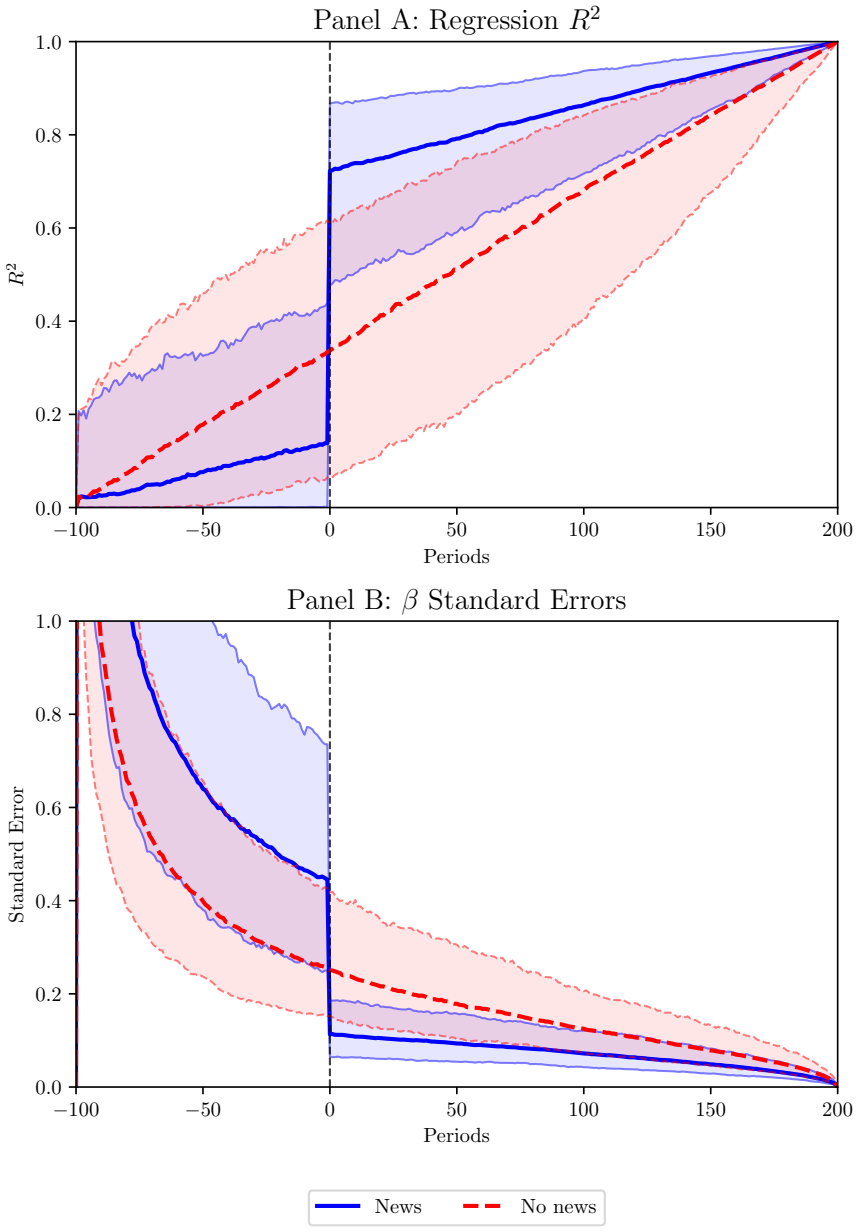


Figure A4. Cumulative Order Imbalance Following FOMC Announcements

This figure shows the mean and median absolute cumulative order imbalance five minutes before to 60 minutes after FOMC announcements with and without scheduled press conference. Order imbalance is defined as the difference between the total number of buys and sells in trade volume (in thousand).