Can Trading Derail Price Discovery? 
Evidence from FOMC Announcements

Oliver Boguth, Vincent Grégoire, and Charles Martineau*

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ABSTRACT
Following Federal Open Market Committee announcements, the S&P 500 updates to unexpected news quickly. Despite fast price adjustments, abnormal trade volume persists. However, this trade flow does not reflect learning about fundamentals. On the contrary, order imbalances derail price discovery for approximately one hour, and cause prices to become less efficient than those immediately after the announcement. The distorting effect of trading persists past the end of the trading day. Our evidence highlights the importance of price pressure at the market level and shows that excessive trading can prevent efficient market prices following the arrival of public news.

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Federal Open Market Committee (FOMC) announcements by the Federal Reserve are some of the most anticipated macroeconomic news. Trading days with FOMC announcements, which occurs eight times per year, are associated with large equity risk premium, significant resolution of uncertainty, and substantial trading activity in financial markets.\footnote{A recent literature shows that most of the equity risk premium is earned on FOMC announcement days (see, e.g., Savor and Wilson, 2013, Lucca and Menich, 2015, Ai and Bansal, 2017, Cieslak, Morse, and Vissing-Jorgensen, 2016, Boguth, Grégoire, and Martineau, 2018).}

The information content of FOMC announcements has profound economic implications, not only for the United States but also worldwide (Brusa, Savor, and Wilson, 2016). Contrary to other macroeconomic announcements (e.g., Employment Situation, Consumer Sentiments), intraday price formation around FOMC announcements remains little understood.\footnote{A large literature documents intraday price formation around macroeconomic news, other than FOMC announcements, for a broad set of asset classes. Important papers in this area include Ederington and Lee (1993), Jones, Lamont, and Lumsdaine (1998), Fleming and Remolona (1999), Balduzzi, Elton, and Green (2001), Andersen, Bollerslev, Diebold, and Vega (2003, 2007), Rosa (2016), Hu, Pan, and Wang (2017), and Chordia, Green, and Kottimukkalur (2017).}

In this paper, we study price formation following FOMC announcements in the equity market. Understanding how information transmits and impounds into market prices is a central question in financial economics, and addressing these issues contributes to our understanding of how financial markets function. Moreover, the substantial trading activity we observe following FOMC announcements raises the question of whether trading around large news events plays a role in the incorporation of public information into asset prices, and more generally to market efficiency, but little is known on how that process works.\footnote{Evans and Lyons (2002) shows at the daily frequency in the currency exchange market that prices are driven by order flow not public information (changes in nominal interest). Grégoire and Martineau (2017) shows that Initial stock price reactions following earnings announcements are explained by earnings surprises (the “news”), not by liquidity-taking order flow.}

The main objective is twofold. First, we quantify how quickly FOMC announcement news incorporates into stock prices, i.e., the speed of price discovery. Second, we investigate if, and how, trading activity following FOMC announcements contributes to price discovery. We compare how announcement returns react to both FOMC announcement surprises and net
order flow to determine if surprises incorporate prices directly or indirectly via the arrival of trades.

Our analysis focuses on FOMC meetings from April 2011 to September 2017, for a total of 52 announcements. April 2011 marked the introduction of press conferences by the Chairperson of the Federal Reserve following the FOMC statement releases for half of the meetings in a given year. Boguth, Grégoire, and Martineau (2018) show that FOMC announcements with press conferences are perceived by investors as more important. Also, because of recent developments in trading technologies affecting market dynamics such as high-frequency trading, using a recent sample is more likely to yield findings relevant to current market design and policy decisions.

We use a non-parametric approach proposed by Biais, Hillion, and Spatt (1999) to estimate the speed of price discovery in the equity market using e-mini S&P 500 futures contracts. The approach relies on regressions of long-horizon announcement returns on short-horizon announcement returns. We first regress the long-horizon announcement returns, computed using the midquote 60 minutes before the announcement to the settlement price on the announcement day, on short-horizon returns computed from the same starting time until some time $t$. Estimating this regression for each minute $t$ around the announcement presents the dynamics in the price discovery process.

We find that price discovery occurs quickly, minutes after the announcement and that price discovery takes place only on FOMC meetings that are followed by press conferences, which are deemed more important. Looking at the pattern of $R^2$, we observe a jump at the announcement to about 60% after 5 minutes. The $\beta$ coefficient estimate also jump slightly close to one at the announcement, indicating fast price reaction.

The previous test implicitly assumes that price discovery is complete in the period covered

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4 Boguth, Grégoire, and Martineau (2018) find greater investor attention to monetary policy news in the days before the announcement, large risk premium and resolution of uncertainty, greater market expectations of a change in interest rates for FOMC announcements accompanied with press conferences.
by the long-horizon return. To test the validity of this assumption, we repeat the test using the settlement price on the following trading day as the end price for our long-horizon returns. Consistent with our previous results, we observe a fast price reaction, with a $R^2$ of about 40% after 5 minutes. However, following this initial burst of price discovery, we observe a pattern of price undiscovery, i.e., divergence from future indicative fundamental prices because prices are noisier. The $R^2$ goes down to below 10% about 50 minutes after the announcement. The $\beta$ coefficients suggest this mispricing is not due to systematic under or overreaction. Furthermore, this pattern is not present in our first test using the same-day settlement price, which suggests that mispricing persists until the next day.

What can explain this pattern of price undiscovery? We hypothesize that price undiscovery is caused by temporary price pressure due to the abnormally large trade volume that occurs following FOMC announcements. Trading can distort price discovery because of limited capacity by liquidity providers at accommodating order flow. In a frictionless world, liquidity providers adjust prices immediately to news and absorb order flow from incoming noise traders. However, in reality, liquidity providers have limited inventory-carrying and risk-bearing capacity (see, Hendershott and Seasholes, 2007, Hendershott and Menkveld, 2014). Moreover, liquidity providers that do accommodate buying or selling pressure will do so only if they can buy (sell) at a discount (premium) relative to future prices.\footnote{The work of Kroencke, Schmeling, and Schrimpf (2017) attributes the abnormal level of trading following FOMC announcements to portfolio rebalancing.} Consistent with this hypothesis, we find that liquidity-taking order flow, i.e., trading, does not contribute significantly to the initial price discovery, but explains most of the observed price undiscovery.

If price discovery is caused by temporary trade imbalance and not fundamental news, the mispricing should be temporary and lead to a predictable reversal. We confirm this by using another set of simple regressions of returns on returns. We find that E-MINI returns between +10 and +50 minutes after the announcement, the period during which the undiscovery
occurs, explain 30% of the variations in returns from +50 minutes to settlement on the next day. The $\beta$ coefficients are negative and significant, which is indicative of a reversal. We confirm with further tests that this predictable reversal begins on the announcement day, but most of it occurs after settlement on the announcement day. Finally, we show that these patterns are not unique to the E-MINI and are also present in S&P 500 returns computed from underlying stock prices.

To test our hypothesis that the temporary mispricing is caused by large order imbalances, we decompose returns following FOMC announcements into two components: returns explained by net order flow and returns not explained by net order flow. We define net order flow as the difference between the volume of buyer- and seller-initiated market orders. We show that price reversals following FOMC announcements are predicted only by the component of returns explained by order imbalance, and not by the residual component. The explanatory power of order imbalance to explain reversals can be as high as 30%. In other words, trading derails price discovery. Our findings reveal that significant market frictions can impede price efficiency even in the most liquid assets. To our knowledge, this paper is the first to document inventory risk for the broad index, the S&P 500, and the first to document the implication of inventory risks for price discovery around the release of public information.

Our last empirical analysis consists of determining whether order flow does contribute to price discovery at the time of the announcement. Our previous results indicate that order flow leads to noisier prices after the announcement. However, at the time of the announcement, order flow may be responsible to the fast price discovery we observe.

To investigate if order flow contributes to price discovery at the time of the announcement, we follow Evans and Lyons (2002) and Grégoire and Martineau (2017) and examine the explanatory power of order flow to explain E-MINI returns relative to a measure of FOMC announcement surprise (unexpected news). We use the signed order-level data from NASDAQ.
TotalView-ITCH on the SPY as a proxy of order flow imbalances in S&P 500-linked instruments. Our measure of unexpected monetary policy news shocks at FOMC announcements is based on changes in Eurodollars futures. Recent macroeconomic papers (e.g., Gurkaynak, Sack, and Swanson, 2005, Gertler and Karadi, 2015, Nakamura and Steinsson, 2017) show that such a measure can capture the effects of “forward guidance” by the Federal Reserve, which consist of information about future changes in the federal fund rate.

Our measure of FOMC surprise explains 55% of the variation in announcement returns, whereas net order imbalance explains 25%. In a joint regression, the $R^2$ increases to 60%, which suggest that order imbalance improves the explanatory power by only 5% relative to the explanatory power of surprises alone. The explanatory power of surprises on subsequent price changes is short-lived; changes in Eurodollars have no impact on equity prices past two minutes following the announcement. This is consistent with our previous results that prices quickly incorporate news at the time of the announcement. Therefore, our results indicate that initial price discovery occurs mainly through news and not order flow. However, the explanatory power of order imbalance remains positive and statistically significant for the entire duration of the trading day, which is consistent with our finding that price undiscovery is driven by order imbalance.

Our paper contributes to the growing literature of intraday price formation around macroeconomic news. Closely related to our paper, Andersen, Bollerslev, Diebold, and Vega (2003, 2007), Hu, Pan, and Wang (2017) and Chordia, Green, and Kottimukkalur (2017) find that price discovery following macroeconomic news occurs rapidly, more or less at the time of the announcement, and in recent years within seconds. Our paper is the first to examine the dynamics in price discovery following FOMC announcements, one of the most, if not the most, important macroeconomic announcements and we also find quick price discovery.

We also contribute to the literature documenting the importance of inventory manage-
ment by liquidity providers and price pressure to explain the dynamics of market liquidity and asset returns. Hendershott and Seasholes (2007) find that specialists are compensated for inventory risk by return reversals when accommodating price pressure and Comerton-Forde, Hendershott, Jones, Moulton, and Seasholes (2010) show that inventories have incremental predictive power for future liquidity. More recently, Hendershott and Menkveld (2014) show theoretically that price pressure can move prices away from fundamentals because of inventory management by liquidity providers and provide empirical results supporting their theories. The findings of this paper highlight the detrimental role of price pressure in price discovery following the arrival of public news.

I. FOMC Sample and Data Description

In this section, we describe our sample and the datasets used.

A. FOMC announcements

The FOMC announcement sample is from April 2011, the first meeting following the introduction of press conferences (PCs), to September 2017. Boguth, Grégoire, and Martineau (2018) show that the introduction of PCs following half of FOMC announcements led to a regime shift in the “news” worthiness of announcements.\(^7\) In short, there are now two types of FOMC announcements, and those with PCs are the most important ones. Our analysis focuses on price formation in this new FOMC regime, and we do find consistent differences between meetings with or without PCs.

We exclude from our analysis the FOMC announcement of August 8, 2011, which occurred at the height of the Eurozone debt crisis and two days after Standard and Poors downgraded the United States credit rating from AAA to AA+. Market activity on the day of the FOMC

\(^7\)We refer the reader to Boguth, Grégoire, and Martineau (2018) for more details on the implication of the introduction of FOMC press conferences on market expectations and news revelation.
announcement was abnormally high compared to other FOMC announcements days.\(^8\) In total, we have 51 FOMC announcements, and 27 of those are followed by a press conference.

We obtain historical FOMC announcements from Thomson Reuters Tick History (TRTH), provided by the Securities Industry Research Centre of Asia-Pacific (SIRCA), with millisecond precision timestamps corresponding to the time the information is released to Thomson Reuters terminals.\(^9\) Table I presents the calendar of FOMC announcements, along with the scheduled and actual release times, and which announcements were followed by a press conference.

To emphasize the importance of using actual timestamps for FOMC announcements and not the scheduled timestamps, Figure 1 shows FOMC announcement release time delays since 2004, in seconds, defined as the time difference between the actual timestamp of the news release and the scheduled time. Clearly, the timeliness of releases improved dramatically in 2013. This coincides with the harmonization of announcement times for meetings with and without PC at 2 p.m. Before 2013, we observe a significant variation in the release delay.

### B. Data

Our analysis focuses on the two most liquid financial products tracking the S&P 500 index: the S&P 500 E-Mini Futures (E-MINI) and the SPRD S&P 500 exchange-traded fund (SPY).\(^10\) We use the E-MINI for most of our analysis and use the SPY when our analysis focuses on the role of order flow and liquidity provision in price formation. Our analysis also uses Eurodollar futures, the most heavily traded product on the Chicago Mercantile Exchange (CME).

We use two intraday databases that contain trades and quotes data. First, we retrieve

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\(^8\) study the impact of the European Central Bank (ECB) communication on the yield curve and similarly exclude the ECB meeting of August 4, 2011, because of monetary policy.

\(^9\) Section A of the Appendix presents a discussion on the accuracy of these timestamps.

\(^10\) 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 E-MINI and SPY prices comove because of high-frequency arbitrageurs.
SPY, E-MINI and Eurodollar futures data from TRTH. The data includes all trades and quotes updates at the best price with millisecond-precision timestamps for SPY and second-precision timestamps for futures. Second, we retrieve NASDAQ order-level data on SPY, also known as NASDAQ TotalView-ITCH. The ITCH data contains all messages distributed through NASDAQ’s high-frequency feed, including messages that describe orders added to, removed from, and executed on NASDAQ. We construct a message-by-message limit order book, where the book is updated when a new message enters the NASDAQ exchange.

The main advantage of ITCH over TRTH or TAQ is that it allows us to accurately sign all trades, except trades against hidden (i.e., non-displayed) limit orders. Trades are not signed in TRTH or TAQ; the researcher must infer if a trade is buyer- or seller-initiated using a trade classification algorithm.\textsuperscript{11} Hidden orders are limit orders that are not visible to other traders, and while we observe trades against hidden orders, NASDAQ stopped signing those trades in the ITCH feed after July 13, 2014. When the empirical analysis requires signed trades, the sample period starts on January 1, 2011, and ends on July 13, 2014. The dataset contains all trades executed on NASDAQ, including the NASDAQ portion of Reg NMS ISO orders and odd-lot orders.\textsuperscript{12}

II. Financial Markets Around FOMC Announcements

In this section, we examine market conditions such as returns, price volatility, and bid-ask spreads around FOMC announcements. This is not the first paper to examine the implication of FOMC announcements on market conditions (see, Lucca and Moench, 2015, Rosa, 2016), but to our knowledge, it is the first to do so conditioning on FOMC announcements with and without press conferences. As shown in Boguth, Grégoire, and Martineau (2018), changes

\textsuperscript{11}These trade classification algorithms are not flawless (see Chakrabarty, Pascual, and Shkilko, 2015). Because volatility is very high following FOMC announcements, it imposes significant constraints on the effectiveness of trade classification algorithms.

\textsuperscript{12}Odd-lot orders are trades with less than 100 shares, can represent up to 60% of the total transactions (O’Hara, Yao, and Ye, 2014), and are not reported to the consolidated tape before December 9, 2013.
in Eurodollars, volatility, and returns at the time of the announcement are larger for FOMC announcements that are followed by press conferences.

A. Market returns

We first look at market returns using E-MINI around FOMC announcements. Figure 2 plots average cumulative E-MINI returns starting 150 minutes before to 90 minutes after FOMC announcements separately for FOMC with and without press conferences. Returns are normalized to zero at the time of the announcement. Panel A shows that, for the full sample, cumulative returns are not statistically different from zero following FOMC announcements. The figure shows that when there is a PC (solid blue line), prices increase by about 0.40% in the hour following the announcement, a result that is economically large and statistically significant. In contrast, FOMC announcements without PCs (dashed red line) are accompanied by an insignificant drop in prices of about 0.30% during a volatile period following the announcement.

The reasons why FOMC meetings with PCs are associated with positive returns is beyond the scope of this paper. However, a fraction of these positive returns are associated with resolution of uncertainty, and therefore, positive risk premium follows. For instance, in Boguth, Grégoire, and Martineau (2018), the authors show that FOMC announcements with PCs are associated with more investor attention to monetary policy leading to the announcement, consistent with recent theoretical and empirical work linking investor attention and risk premia (see, Andrei and Hasler, 2014, Fisher, Martineau, and Sheng, 2017).

B. Trade volume

We next examine abnormal trade volume around FOMC announcements at daily and intraday horizons. For looking at daily figures, we regress the daily abnormal trade volume $AV_t$ on PC and non-PC indicator variables $1_{PC,t}$ and $1_{non-PC,t}$ equal to one if date $t$ is a PC day or
a non-PC day, respectively, and zero otherwise, and on ten leads and lags of the indicators variables:

\[ AV_t = \alpha + \sum_{i=-10}^{10} \beta_{PC,i} 1_{PC,t+i} + \sum_{i=-10}^{10} \beta_{non-PC,i} 1_{non-PC,t+i} + \varepsilon_t. \tag{1} \]

We define abnormal trading volume as the difference between the log daily trading volume and the average log daily trading volume over the three months period ending 15 trading days before the observation date. We include weekday fixed effects, and compute standard errors using the Newey-West estimator. The sample period includes all trading days from April 2011 to September 2017.

Figure 3 shows coefficient estimates and their associated 95% confidence intervals. Results indicate that there is an important difference between the patterns for PC and non-PC meetings. For meetings with PC, trading volume becomes abnormally high starting the day before the announcement, is about 32% larger on the announcement day than during the benchmark period, and remains significantly high for over a week following the announcement. In contrast, on meetings without PC, abnormal daily volume is positive from two days before the announcement, but with a much smaller magnitude and drops back to normal the day after the announcement. Furthermore, the coefficient estimate on the day of the announcement is not statistically significant at the 5% level. Finally, we find that while none of them are individually significant at the 5% level, all coefficients for PC ten to four days before the announcement are negative, suggesting that trading is lower on average during the two weeks before those meetings.

Figure 4 shows the average trading volume for one-minute intervals in event time for all e-mini contracts from 2.5 hours before to 1.5 hours after the FOMC announcement. The time interval is chosen to avoid potential effects from overnight returns.\(^{13}\) We show the mean trade volume for FOMC announcements with press conferences (solid blue line) and those without

\(^{13}\)As shown in Table I, prior to 2013, announcements with PCs were made no earlier than 12:27 p.m., or 2 hours and 57 minutes after market open, and between August 2011 and January 2013 announcements without PCs were made no later than 2:23 p.m., or 1 hour and 37 minutes before market close.
(dashed red line), and on the ten trading days before each announcement (dotted cyan line). The shaded areas are the pointwise 95% confidence bands.

The emerging pattern in trading volume is a jump at the announcement followed by gradual decay. Trading volume remains abnormally high throughout the rest of the trading day for both FOMC with PC and non-PC. Volume appears to be slightly larger on PC days than on non-PC days.

One limitation of our sample is that announcement times vary throughout our sample period, preventing us from observing calendar time patterns over the full sample. Nonetheless, since March 2013 announcements have been scheduled for and released at 2 p.m. (see Table I and Figure 1). Figure 5 presents the average trading volume per 1-minute interval in calendar time for the subsample beginning with the March 2013 meeting and ending in September 2017. First, intraday trading volume before the announcement is not significantly different from the benchmark. After the announcement, the difference between PC and non-PC days is larger in this later sample. Trading volume spikes at 4 p.m. at the closing of the market, followed by a smaller spike in E-MINI during the settlement period from 4:14:30 p.m. to 4:15:00 p.m. Trading in E-MINI is negligible after the daily trading halt, while it remains significantly higher for the SPY in the after-hours market.

Overall, our evidence suggests that trading volumes are high not only immediately after the announcement but also on the day before and the following trading days. Furthermore, trading volume is also significantly higher on days with PCs than on those without.

C. Spreads

We conclude our discussion of the trading environment by looking at the variations in bid-ask spreads around FOMC announcements. Wider spreads are typically associated with lower liquidity or more informational asymmetry between liquidity providers and liquidity takers (Glosten and Milgrom, 1985). The E-MINI and SPY are very liquid instruments that usually
trade at the minimum spread allowed by discrete trading ticks: 0.25 points (where the quoted unit is in index points) for the E-MINI and $0.01 for the SPY.

Figure 6 shows average spreads for E-MINI and SPY in the eight-minutes window centered at the announcement. Both the E-MINI and SPY are trading at the minimum spread at the beginning of the window four minutes before the announcement. First looking at meetings with PC, we observe an increase in the average spreads starting about three minutes before the announcement, a peak at the announcement, and a rapid decrease afterward. Interestingly, the magnitude of the spreads varies significantly. For the E-MINI, the spread peaks at over 0.8. After three minutes, spreads are almost back to normal. This speaks a lot about the liquidity of these instruments: following a large informational shock and in the presence of high trading volume and volatility, spreads returns to their benchmark values within few minutes.

III. The Speed of Price Discovery

We begin our analysis by estimating the speed of price discovery following FOMC announcements. We follow the methodology of Biais, Hillion, and Spatt (1999) to study the dynamics of price discovery following FOMC announcements. Let \( v \) be the true value of the S&P 500 E-MINI futures and the price at time \( t \) on event \( i \) be a reflection of all the information incorporated by the market up to time \( t \):

\[
p_{i,t} = E(v|I_{i,t}).
\]  

(2)

We measure price discovery at time \( t \) with the following regression equation around FOMC announcements:

\[
r_{i,-60,t} = \alpha_t + \beta_t r_{i,-60,t} + \varepsilon_{i,t},
\]

(3)

where \( r_{i,[t_1,t_2]} = \log(p_{i,t_2} - p_{i,t_1}) \) is the log return from time \( t_1 \) to time \( t_2 \) for event \( i \). Time is measured in minutes, with \( t = 0 \) corresponding to the announcement time. Because not
all announcements are made at the same time, we use \( T \) and \( T + 1 \) to denote the futures settlement time on the day of the announcement and the following day, respectively, and use those times as the end time \( t^* \).

The speed of learning can be observed through estimated \( \beta \) coefficients and regressions \( R^2 \)'s. If the price at time \( t \) is an unbiased estimate and informative of the fundamental value, we expect to find \( \beta \) equal to one. Even on FOMC days, stock returns are affected by information unrelated to FOMC news. Therefore, the level of \( R^2 \) at any point in time cannot be interpreted as a measure of the amount of FOMC news that is included in prices, but time series patterns of \( R^2 \) are informative about the type of information being incorporated into prices. We expect the \( R^2 \) to be strictly increasing over time, with the slope indicating the instantaneous speed of price discovery.\(^{14}\)

Panels A and B of Figure 7 show \( \beta \) coefficient estimates and regressions \( R^2 \)'s for the regressions using returns up to the settlement time on the announcement day \( (t^* = T) \). The shaded areas are pointwise 95% bootstrapped confidence bands around the \( \beta \) estimates and \( R^2 \)'s. The \( R^2 \) jumps at the announcements, going from 0 to over 60% in less than five minutes. At the same time, the \( \beta \) becomes significantly different from 0, indicating that returns after the announcement are good predictors of total returns. The \( \beta \) increases above 1, and stays significantly different from 1 for about 20 minutes, suggesting a small, short-lived underreaction. During that time, the \( R^2 \) moves without direction before increasing steadily towards 1.\(^{15}\)

Panels C and D of Figure 7 show \( \beta \) coefficient estimates and regressions \( R^2 \)'s for the regressions using returns up to the settlement time on the day following the announcement \( (t^* = T + 1) \). The immediate reaction tells the same story as the previous plots with end time \( t^* = T \). The \( R^2 \) jumps to 40% at the announcement, and the \( \beta \) becomes statistically

\(^{14}\)See Grégoire and Martineau (2017) for more details.

\(^{15}\)If all announcements occurred at the same time, the \( R^2 \) would reach one at settlement time. In our setup, returns are not aligned, and the figure ends at \( t = 135 \) which correspond to 4:15 p.m. (end of the 30-seconds settlement period for E-MINI futures) for announcements at 2:00 p.m.
different from zero, indicating a similar underreaction. However, this is where similarities end. After this initial burst of price discovery, when returns after 10 minutes explain 40% of returns ending the next day, price discovery derails, and the $R^2$ decreases to less than 10% at 50 minutes after the announcement. Consequently, the $\beta$ coefficient is not statistically significantly different from 0 following what appears to be price “undiscovery”. However, the coefficient estimate is very close to one, ruling out systematic under-reaction and over-reaction. A little over two hours later ($t = 135$), the $R^2$ is back to the level it was moments after the announcements. Panels E and F show the same results, extending the window by 24 hours. The big dip in price discovery until settlement is followed by a flat period during the after-hours period,\textsuperscript{16} and price discovery resumes shortly before markets open.\textsuperscript{17}

**IV. Derailing Price Discovery**

Results presented in the previous section raise two new questions. First, why do we observe price undiscovery when using the next day settlement as our final price, but not when using the announcement day settlement price? Second, what could be derailing price discovery? We next show that this unlearning is the result of temporary mispricing that is not fully resolved by settlement time on the announcement day, and this mispricing generates predictable returns reversals. We then show that this mispricing can be tied to order imbalance, and we argue that it is caused by large liquidity demands that liquidity providers are not able to accommodate in a timely fashion.

\textsuperscript{16}Regular trading hours for equity markets are from 9:30 a.m. to 4 p.m., but trading also occurs during extended trading hours, also know as the after-hours market, from 4 p.m. to 8 p.m. and 4 a.m. to 9:30 a.m. E-MINI futures trade continuously from Sunday to Friday, with a trading halt on CME Globex from 4:15 p.m. to 4:30 p.m. Figure 7 uses E-MINI midquotes, and we pad the missing values resulting from the halt with the latest pre-halt midquotes.

\textsuperscript{17}For announcements at 2 p.m., the next day opening of markets occurs at $t = 1,170$. 

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A. Markets reversals and predictability

Results presented in Figure 7 suggest that there is price discovery and undiscovery following FOMC announcements, but that it is not due to systematic under-reaction or overreaction. For the $R^2$ in Panel D to decrease significantly while the $\beta$ in Panel C converges to one, there must be a source of temporary noise orthogonal to announcement returns that is resolved by the end of the following day but not by settlement time on the announcement day. If that is the case, there should be predictability in E-MINI futures returns during that period. We investigate this predictability using variations on regression (3).

Intuitively, if some temporary mispricing appears after the initial price discovery and is resolved by the end of the next day, we can use returns over the period mispricing enters prices to predict the following reversal. The pattern in Panel D of Figure 7 suggests that initial price discovery is complete within 10 minutes and that the magnitude of subsequent mispricing peaks around the 50 minutes mark. We thus run the following regression for each minute $t$ between 25 and 105 minutes following the announcement:

$$r_{i,[t,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \varepsilon_{i,t},$$  \hspace{1cm} (4)

where $r_{i,[10,t]}$ is the return between 10 minutes after the announcement and time $t$, and $r_{i,[t,T+1]}$ is the return between time $t$ and the settlement price on the following day.

Panels A and B of Figure 8 present $\beta$ coefficient estimates and regressions $R^2$s for the reversal regressions. The emerging patterns tell a compelling story. First, returns after announcements do reverse, with a peak of $R^2$ around $t = 50$ minutes, which corresponds to the peak of price undiscovery. Results show that returns from 10 minutes to 50 minutes after the announcement explain over 30% of the variation in returns from 50 minutes until settlement on the next day. The negative coefficient estimates indicate that it is a reversal, and the coefficient of $-2$ suggests that the mispricing is larger than the returns measured from $+10$ to $+50$ minutes. A possible explanation is that the mispricing appears before that
point in time, but measuring it is complicated by large price movements during the initial phase of price discovery. We confirm in untabulated results that when using $t = +1$ instead of $t = +10$ for the starting point, the $\beta$ estimate at $t = +50$ is very close to one, but the estimate is barely statistically significant at the 95% level.

To verify that we are not capturing high-frequency reversal, we next estimate a slightly modified version of the previous regression, replacing the left-hand side by the next day return:

$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \epsilon_{i,t}.$$  

Results presented in Panels C and D confirm that most of the reversal occurs on the next day and that the mispricing survives beyond the initial market closing auction and futures settlement period. However, we note that the magnitude of coefficient estimates in Panel C is smaller than in Panel A, which suggests that some of the reversal occurs on the announcement day.

We tests this insight using the following regression:

$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[t,T]} + \epsilon_{i,t},$$  

where $r_{i,[t,T]}$ is the return from time $t$ to the settlement period on the announcement day. Results are presented in Panels E and F. Past the 50 minutes mark, coefficient estimates are positive and statistically significant, which confirm that returns toward the end of the announcement day are positively related to returns on the following day.

B. Price pressure and individual stock prices

Our results so far show that there is an important mispricing in E-MINI futures following FOMC announcements caused by order imbalance. While the E-MINI futures is the most liquid instrument for trading in the S&P 500 index, it is not per se the index, and it is not clear that our results generalize to the cross-section of stocks. We verify that individual
stocks are also affected by repeating the tests in Section A using S&P 500 index returns, which are computed from underlying stock prices. Consequently, we also redefine times $T$ and $T+1$ as the S&P 500 closing price on the announcement day and the following day. Results presented in Figure 9 confirm that those effects are not specific to E-MINI and are present in S&P 500 underlying stocks.

C. The role of order imbalance in derailing price discovery

Results from the previous section show that FOMC announcements are followed by a period of increasing mispricing that starts to revert about 50 minutes after the announcement but is not fully resolved until the following day. We hypothesize that this temporary mispricing is caused by demands for liquidity, i.e., that the very large trading volume, and the associated order imbalance, is too large for liquidity providers to accommodate within their inventory constraints. While we cannot observe liquidity providers inventory positions, we can observe signed order flow for the SPY ETF on NASDAQ.

We first decompose returns into two components using the following regression estimated at two-minute intervals $t$:

$$r_{i,t} = \alpha + \gamma_0 OI_{i,t}^N + \gamma_1 OI_{i,t} + \gamma_2 TV_{i,t} + \gamma_3 OI \times TV_{i,t} + \gamma_4 OI_{i,t-1}^N + \gamma_5 OI^N \times TV_{i,t-1} + \epsilon_{i,t} \quad (7)$$

where $r_{i,t}$ is the log return over interval $t$ for announcement $i$, and $OI_{i,t}$ is the order imbalance defined as the volume of buyer-initiated trades minus the volume of seller-initiated trades,$^{18}$ $TV_{i,t}$ is the total trade volume, and $OI_{i,t}^N$ is $OI_{i,t}$ divided by $TV_{i,t}$. We then use the estimated coefficients to decompose returns into the part predicted by order imbalance and the residual component orthogonal to it. The overall average $R^2$ of 2-minute regressions is 52%, which suggests that the total variation of each component is roughly the same.

$^{18}$We use SPY in the ITCH dataset instead of E-MINI to compute order imbalance and total volume because we only have signed order flow for SPY. For our results to be general, 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.
We next use these two components to estimate modified versions of regression (4):

\[ r_{i,[t,T+1]} = \alpha_t^{\text{Pred}} + \beta_t^{\text{Pred}} \hat{r}_{i,[10,t]} + \varepsilon_t^{\text{Pred}}, \]  

(8)

\[ r_{i,[t,T+1]} = \alpha_t^{\text{Res}} + \beta_t^{\text{Res}} \hat{\epsilon}_{i,[10,t]} + \varepsilon_t^{\text{Res}}, \]  

(9)

where \( \hat{r}_{i,[10,t]} \) is the part of returns between 10 minutes after the announcement and time \( t \) explained by order imbalance and \( \hat{\epsilon}_{i,[10,t]} \) is the part orthogonal to order imbalance.

Results are presented in Panels A and B of Figure 10. Both panels tell the same story: only the component of returns predicted by order imbalance explains returns reversals. The \( \beta \) coefficients for predicted returns are of similar magnitude to those in Panel A of Figure 8, while the \( R^2 \) are slightly lower than those in Panel B of the same figure, peaking at about 20\%.

Finally, we repeat the exercise by replacing the left-hand side of the regression by next-day returns as in regression (5). Results are presented in Panels C and D of Figure 10. Results are consistent with those in the first two panels, and the \( R^2 \) associated with order imbalance predicted returns are higher, peaking at more than 30\%. Overall, our results indicate that returns reversals following FOMC announcements are explained by order imbalance in the hour following announcements and that trading derails price discovery.

V. Does Order Flow Contribute to Price Discovery?

The evidence presented in the previous section suggests that trading derails the price discovery process following the initial reaction to FOMC announcements. In this section, we investigate the role of order flow in this initial price reaction. To do so, we follow the literature and compare the explanatory powers of order imbalance and a measure of surprise (“the news”). We first present our measure of FOMC announcement surprise and then show that the immediate price reaction is mostly explained by the surprise, not by the order imbalance. However, returns during the price undiscovery period are mostly explained by order flow,
which is consistent with our results from the previous section.

A. Announcement surprises

Prior literature has used the difference between the announced Fed fund target rate and analysts expectations (e.g., Andersen, Bollerslev, Diebold, and Vega, 2003), 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. These measures are not appropriate in the sample period we are studying for two reasons. First, the Fed fund rate is quite stable in our sample, with only one highly anticipated rate increase, so analysts are always right and the implied Fed fund rate from futures does not react much to the announcement. Second, that period was uniquely defined by the wide use of non-conventional monetary policy tools, and the resulting information content of FOMC announcement goes beyond the target rate number.

We follow Nakamura and Steinsson (2017) and Boguth, Grégoire, and Martineau (2018) and use changes in Eurodollar futures around FOMC announcements as a measure of surprise. Eurodollar futures are the most liquid contracts traded on the CME. These derivatives react strongly to FOMC announcements and have been used as measures of announcement surprises in prior literature (e.g., Gurkaynak, Sack, and Swanson, 2005, Gertler and Karadi, 2015, Nakamura and Steinsson, 2017, Boguth, Grégoire, and Martineau, 2018). Their settlement price is 100 minus the three-months spot London interbank offered rate (LIBOR) at maturity, and quarterly contracts trade with up to ten years 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 (2018) for more details on the interpolation procedure.

Our measure of surprise is based on the changes in implied LIBOR rate for different maturities from 1 minutes before the announcement to different time horizons following the
announcement. We make use of Eurodollar futures with maturities of \( q \) quarters in the future, where \( q = 2, 4, 6, \) and 12, which we denote as ED2, ED4, ED6, and ED8.

An important step to construct our measure of surprise to FOMC announcement is to choose the time window around FOMC announcements to measure the change in Eurodollar futures contract. We undertake this step in the next section.

A.1. Determining the window length for changes in Eurodollar

We determine the best window length to measure FOMC announcement surprises with Eurodollar around FOMC announcements using a regression of E-MINI returns on each Eurodollar rate changes around FOMC announcements with expanding window lengths. Formally,

\[
Ret_t = \alpha + \beta ED_{q,t} + \epsilon_t,
\]

where \( Ret_t \) is the return from one minute before FOMC announcements to \( t \) minutes after the announcement and \( ED_{q,t} \) is the change in the Eurodollar rate of maturity \( q \) over the same period. Figure 11, shows the explanatory power \( (R^2) \) from the above regression using different time windows. The largest explanatory power of changes in Eurodollar contracts on equity returns occurs at two minutes following FOMC announcements, with an \( R^2 \) of approximately 50\%.

\(^{19}\) Consequently, in the remaining analysis of this paper, we use changes in Eurodollars starting one minute before the FOMC announcement and ending two minutes after.

Similarly to Nakamura and Steinsson (2017), we construct our measure of FOMC announcement surprise as the first principal component of the change in the four Eurodollar maturities over the same time window, which we denote as 1\(^{st}\) Comp. In Table II, we present the mean, the standard deviation, percentiles and correlation on the five FOMC announcement surprises using Eurodollars and the E-MINI return over the same time interval. It is

\(^{19}\)Repeating this exercise using SPY returns rather than E-MINI yields quantitatively similar results.
important to highlight the high pairwise correlations between the four Eurodollar returns. We find that the first principal component explains 95% of the variation in Eurodollars. Also, we note the high negative correlation between equity returns and the changes in Eurodollars of approximately -0.74.

As explained in the previous sections, distinguishing between FOMC with and without schedule press conferences is important. Boguth, Grégoire, and Martineau (2018) show that changes in Eurodollars around FOMC announcements are greater on FOMC announcement days with scheduled press conferences, which are also accompanied by economic projection materials. Table III shows the average absolute returns for Eurodollar contract and the first principal component on FOMC announcement days with and without press conferences. Generally, Eurodollar absolute returns are significantly larger on FOMC announcement days with press conferences.

A.2. FOMC announcement surprises and their impact on equity prices

We next estimate an OLS regression to assess the impact of changes in Eurodollars on E-MINI returns in the interval from one minute before to two minutes after FOMC announcements. Table IV presents results for E-MINI (Panel A) and SPY (Panel B). First, the results between Panel A and B are quantitatively similar. All coefficients are statistically significant and negative at the 1% level with $R^2$'s between 52% to 63%. The Eurodollar with the shortest maturity, ED2, has the largest impact on returns with a coefficient of -0.081. A one standard deviation increase (0.027) in ED2 impacts negatively E-MINI returns by 0.22%. The magnitude of the coefficients decreases in Eurodollar futures for longer maturities but as we show in Table II Panel A, the standard deviation of in Eurodollar returns increases with maturity. A one standard deviation increase (0.082) in the first principal component of Eurodollars also impacts negatively E-MINI returns by 0.22%.
B. The role of order flow in price formation

To evaluate the impact of trade on price formation, we follow previous papers in the microstructure literature (e.g., Evans and Lyons, 2002, 2008, Pasquariello and Vega, 2007) and construct a measure of order flow. We define the order flow imbalance measure (OI) as the difference between the volume of buyer- and seller-initiated trades; it is a measure of net buying pressure.\(^\text{20}\) In many microstructure models, order flow conveys information that liquidity providers need to aggregate. At the time of FOMC announcements, this information may pertain to differential interpretation of the FOMC news. Liquidity providers may not be sophisticated enough to process FOMC news and adjust prices accordingly. Consequently, liquidity providers rely on incoming order flow to adjust prices.

Table V presents the results from OLS regressions of SPY ETF returns on our measure of FOMC surprises and order flow imbalance. Panel A shows results for regressions of equity returns at every two-minute intervals, up to 20 minutes following FOMC announcements, on the first principal components of changes in Eurodollars only. The first two-minute returns are calculated using equity prices one minute before the announcement to two minutes after the announcement. Regression results show that the FOMC surprise has no impact on returns after the first two-minute interval. We can conclude that FOMC surprises incorporate prices rapidly.

Panel B of Table V shows results for a similar regression framework as in Panel A, but using our measure of order flow imbalance as an independent variable instead of the surprise. Not surprisingly, and consistent with previous literature (e.g., Chordia, Roll, and Subrahmanyam, 2002, 2008), order flow positively impacts returns. This relationship holds for all time intervals following FOMC announcements. Note that the \(R^2\) in the first time interval is 25\%, less than the 55\% of the impact of FOMC news from Panel A.

We then regress the equity returns on both FOMC news and the order flow imbalance

\(^{20}\) We have similar quantitative results if we use the number of buys and sells in trade units.
and present the results in Panel C. In the first interval, the coefficient of FOMC news (ED) remains statistically significant and negative, and the order imbalance (OI) remains positive and statistically significant. The R² is 66%, an increase of 5% relative to the univariate regression of returns on FOMC news.

We further test different model specifications for the joint impact of surprises and order imbalance to explain return. It is possible that our measure of order imbalance can have better explanatory power if normalized or that order imbalance has a larger impact on prices conditioned on the total trade volume following the announcement. Panel D presents the regression results of the following model specifications:

\[ r_{i,t} = \alpha + \beta ED_{i,t} + \gamma_0 OI_{i,t}^N + \gamma_1 OI_{i,t} + \gamma_2 TV_{i,t} + \gamma_3 OI \times TV_{i,t} + \gamma_4 OI_{i,t-1} + \gamma_5 OI^N \times TV_{i,t-1} + \epsilon_{i,t}, \]

where \( OI^N \) is a normalized measure of order imbalance, that is, net order imbalance (OI) divided by total trade volume (TV). Panel D shows that at the time of the announcement, any of the measures of order imbalance, trade volume, and the interaction terms are significant. Only the surprise itself drives returns.

We conclude that at the time of the announcement, prices are largely driven 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 derails price discovery.

**VI. Conclusion**

In an efficient market, prices reflect underlying fundamentals. This insures that market prices provide accurate signals for resource allocation to the most productive areas of the economy (Fama, 1970). Moreover, investors benefit from trading at prices that they know are not subject to forces that have little or nothing to do with the fundamental value of the
asset (Kraus and Stoll, 1972).

The goal of the research on which this paper report is to deepen our understanding of price formation in the equity market following FOMC announcements and to assess the role of trade volume in the price formation process. To that end, we document that fundamental monetary policy surprises contained in FOMC announcement statements incorporate equity prices rapidly, within two minutes following the statement release. We further show that large incoming order flow following announcements does not contribute to price discovery but derails it. Incoming order flow pushes prices away from fundamentals, and this temporary mispricing is not corrected until the following trading day. We argue that liquidity providers facing inventory risks are unable to accommodate the extreme buying or selling pressure following FOMC announcements and, therefore, large incoming order flow pushes prices away from fundamental value.

The patterns in price formation following FOMC announcements and its determinants are relevant to for portfolio management applications that involve minimizing transaction costs. Fast price discovery following FOMC announcements does not imply that a manager can trade at an efficient price following the announcement. If the manager trades in the same direction as the incoming order imbalance, she will incur higher transaction costs because she will have traded at an inefficient price.

Our results also have implications for policymakers involved in financial market architecture. We question why FOMC announcements occur during trading hours. It may be more appropriate for FOMC announcements to happen after regular trading hours just like earnings announcements or for policymakers to resume trading following the announcement through frequent-batch auctions to mitigate market price inefficiency. Doing so would 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.
References


Boguth, Oliver, Vincent Grégoire, and Charles Martineau, 2018, Shaping expectations and coordinating attention: The unintended consequences of FOMC press conferences, Working Paper, Arizona State University, Tempe, AZ.


Chordia, Tarun T., T. Clifton Green, and Badrinath Kottimukkalur, 2017, Rent seeking by low latency traders: Evidence from trading on macroeconomic announcements, Working Paper, Emory University, Atlanta, GA.


Cieslak, Anna, Adair Morse, and Annette Vissing-Jorgensen, 2016, Stock returns over the FOMC cycle, Working Paper, University of California at Berkeley, Berkeley, CA.


Grégoire, V., and C. Martineau, 2017, How is earnings news transmitted to stock prices?, Working paper, University of Toronto, Toronto, ON.


Figure 1. FOMC Release Delay

This figure shows the FOMC announcement release delay, in seconds, relative to the official scheduled release time. A negative (positive) number indicates an early (late) release. The sample period is June 2004 to September 2017.
Figure 2. Returns around FOMC Announcements

This figure shows the average cumulative log returns for the shortest maturity E-MINI, in percent, around FOMC announcements in event time. Announcements are separated in those with press conferences (solid blue line) and those without (dashed red line). The shaded areas are pointwise 95% confidence bands around the average return. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.
Figure 3. Daily Trade Volume Around FOMC Announcements

This figure shows estimates from the OLS regression:

\[ AV_t = \alpha + \sum_{i=-10}^{10} \beta_{PC,i} 1_{PC,t+i} + \sum_{i=-10}^{10} \beta_{non-PC,i} 1_{non-PC,t+i} + \varepsilon_t, \]

where \( AV_t \) is the abnormal log daily trading volume in e-mini on date \( t \). \( 1_{PC,t} \) and \( 1_{non-PC,t} \) are PC and non-PC indicator variables equal to one if date \( t \) is a PC day or a non-PC day, respectively, and zero otherwise. Abnormal trading volume is defined as the difference between the log daily trading volume and the average log daily trading volume over the three months period ending 15 trading days before the observation date. We include day-of-the-week fixed effects, and estimate Newey-West adjusted standard errors. Coefficient estimates associated with PC days and their associated 95% confidence intervals are represented in blue circles joined by a dashed line, while those for non-PC days are represented by red squares joined by a dotted line. The sample period includes -10 to +10 trading days around each FOMC announcements from April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.

\[
\begin{align*}
\text{Intercept: } & -0.132^{***} \\
\text{Adj. } R^2: & 0.114 \\
\text{N. Obs.: } & 1639
\end{align*}
\]
Figure 4. Trade Volume around FOMC Announcements

This figure shows the average intraday trading volume per minute for e-mini (all maturities) in Panel A and for the spy consolidated tape in Panel B around FOMC announcements in event time. Announcements are separated in those with press conferences (blue solid line) and those without (red dashed line), and the average volume over the ten trading days prior to each announcement is also presented (cyan dotted line). The shaded areas are pointwise 95% confidence bands around the average volume. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.
Figure 5. Trade Volume around FOMC Announcements in Calendar Time

This figure shows the average intraday trading volume per minute for e-mini (all maturities) in Panel A and for the spy consolidated tape in Panel B on FOMC announcement days between 7 a.m. and 7 p.m. Eastern Time. Announcements are separated in those with press conferences (solid blue line) and those without (red dashed line), and the average volume over the ten trading days prior to each announcement is also presented (dotted cyan line). The shaded areas are pointwise 95% confidence bands around the average volume. The sample period is March 2013 to September 2017. We exclude the FOMC meeting of August 9, 2011. Data are from TRTH.
This figure shows the average intraday spread for the shortest maturity e-mini in Panel A and for the spy consolidated tape in Panel B around FOMC announcements in event time. Announcements are separated in those with press conferences (solid blue line) and those without (dashed red line), and the average spread over the ten trading days prior to each announcement is also presented (dotted cyan line). The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011. Data are from TRTH.
Figure 7. E-Mini price discovery regressions

This figure shows coefficient estimates (Panels A, C and E) and $R^2$s (Panels B, D and F) from the regressions:

$$r_{i,[-60,t^*]} = \alpha_t + \beta_t r_{i,[-60,t]} + \varepsilon_{i,t},$$

where $r_{i,[-60,t]}$ is the E-MINI log return from 60 minutes before the announcement to time $t$ on FOMC announcement day $i$. The terminal price $t^*$ is the settlement price on the announcement day in Panels A and B and on the next day in Panels C to F. The shaded areas are pointwise bootstrapped 95% confidence intervals around the estimated $\beta$ coefficients. and $R^2$s For each regression estimated at each time $t$, there are 27 observations of FOMC meetings with press conferences between April 2011 and September 2017.
Figure 8. Reversals and returns predictability

This figure shows $\beta$ coefficient estimate and $R^2$s from the following regressions:

$$r_{i,[t,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \varepsilon_{i,t}$$ in Panels A and B,
$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \varepsilon_{i,t}$$ in Panels C and D,
$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[t,T]} + \varepsilon_{i,t}$$ in Panels E and F,

where $r_{i,[t_1,t_2]} = \log(p_{i,t_2} - p_{i,t_1})$ is the E-MINI log return from time $t_1$ to time $t_2$ for event $i$. Unit on the x-axis are in minutes, with $t = 0$ corresponding to the FOMC announcement. Because not all announcements are release at the same time, we use $T$ and $T + 1$ to denote the settlement time on the day of the announcement and on the following day, respectively. The shaded areas are pointwise bootstrapped 95% confidence intervals around the estimated $\beta$ coefficients and $R^2$s. For each regression estimated at each time $t$, there are 27 observations of FOMC meetings with press conferences between April 2011 and September 2017.
Figure 9. S&P 500 reversals and returns predictability

This figure shows $\beta$ coefficient estimate and $R^2$s from the following regressions:

$$r_{i,[t,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \epsilon_{i,t}$$ in Panels A and B,
$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[10,t]} + \epsilon_{i,t}$$ in Panels C and D,
$$r_{i,[T,T+1]} = \alpha_t + \beta_t r_{i,[t,T]} + \epsilon_{i,t}$$ in Panels E and F,

where $r_{i,[t_1,t_2]} = \log(p_{i,t_2} - p_{i,t_1})$ is the S&P 500 Net Total Return index log return from time $t_1$ to time $t_2$ for event $i$. Time is measured in minutes, with $t = 0$ corresponding to the announcement time. Because not all announcements are made at the same time, we use $T$ and $T + 1$ to denote the closing time on the day of the announcement and on the following day, respectively. The shaded areas are pointwise bootstrapped 95% confidence intervals around the estimated $\beta$ coefficients, and $R^2$s. For each regression estimated at each time $t$, there are 27 observations of FOMC meetings with press conferences between April 2011 and September 2017.
Figure 10. Order flow and returns predictability

This figure shows $\beta$ coefficient estimate and $R^2$s from the following regressions:

\[
\begin{align*}
    r_{i,[t,T+1]} &= \alpha_t^{\text{Pred}} + \beta_t^{\text{Pred}} \hat{r}_{i,[10,t]} + \varepsilon_{i,t}^{\text{Pred}} \quad \text{in Panels A and B,} \quad (12) \\
    r_{i,[t,T+1]} &= \alpha_t^{\text{Res}} + \beta_t^{\text{Res}} \hat{\varepsilon}_{i,[10,t]} + \varepsilon_{i,t}^{\text{Res}} \quad \text{in Panels C and D,} \quad (13)
\end{align*}
\]

where $r_{i,[t_1,t_2]} = \log(p_{i,t_2} - p_{i,t_1})$ is the E-MINI log return from time $t_1$ to time $t_2$ for event $i$, $\hat{r}_{i,[10,t]}$ and $\hat{\varepsilon}_{i,[10,t]}$ are the predicted values and residuals from regression Equation (11). Unit on the x-axis are in minutes, with $t = 0$ corresponding to the FOMC announcement. Because not all announcements are release at the same time, we use $T$ and $T + 1$ to denote the settlement time on the day of the announcement and on the following day, respectively. The shaded areas are pointwise bootstrapped 95% confidence intervals around the estimated $\beta$ coefficients and $R^2$s. For each regression estimated at each time $t$, there are 27 observations of FOMC meetings with press conferences between April 2011 and September 2017.
Figure 11. Regression of EMinis Returns on Eurodollar Returns

This figure shows the $R^2$ from an OLS regression of emini S&P futures returns on Eurodollar futures returns of different maturity at different time intervals following the FOMC announcement. The returns are calculated using the midpoint one minute before the FOMC announcement to different time intervals following the announcement. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.
Table I
FOMC Announcement Calendar

This table shows the scheduled and actual time at the millisecond precision of FOMC announcements between April 2011 and September 2017.

Source: http://www.federalreserve.gov/monetarypolicy/fomccalendars.htm and TRTH.

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<td>14:00:00.435</td>
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<td>02/01/2017</td>
<td>14:00</td>
<td>14:00:00.372</td>
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<tr>
<td>12/18/2013*</td>
<td>14:00</td>
<td>14:00:01.012</td>
<td>03/15/2017*</td>
<td>14:00</td>
<td>14:00:00.321</td>
</tr>
<tr>
<td>01/29/2014</td>
<td>14:00</td>
<td>14:00:03.009</td>
<td>05/03/2017</td>
<td>14:00</td>
<td>14:00:00.465</td>
</tr>
<tr>
<td>03/19/2014*</td>
<td>14:00</td>
<td>14:00:01.649</td>
<td>06/14/2017*</td>
<td>14:00</td>
<td>14:00:00.624</td>
</tr>
<tr>
<td>04/30/2014</td>
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<td>09/20/2017*</td>
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<td>14:00:01.189</td>
</tr>
</tbody>
</table>

* The FOMC announcement is followed by a press conference by the Chairperson of the Federal Reserve.

† This FOMC announcement is excluded from the analysis for reasons explained in the main text.
Table II
Summary Statistics on Monetary News Shock

This table presents the summary statistics on Eurodollar futures contract returns and S&P 500 returns one minute before to two minutes after FOMC announcements. ED2, ED4, ED6, and ED8 correspond to Eurodollar futures at the different quarterly horizon. 1st Comp. is the first component of a principal component analysis among the four Eurodollar returns. We use the e-mini futures contract to calculate the S&P returns. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.

### Panel A: Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>ED2</th>
<th>ED4</th>
<th>ED6</th>
<th>ED8</th>
<th>1st PC</th>
<th>S&amp;P Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.002</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.027</td>
<td>0.040</td>
<td>0.046</td>
<td>0.052</td>
<td>0.082</td>
<td>0.003</td>
</tr>
<tr>
<td>P25</td>
<td>-0.011</td>
<td>-0.012</td>
<td>-0.012</td>
<td>-0.016</td>
<td>-0.038</td>
<td>-0.001</td>
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<tr>
<td>P50</td>
<td>0.000</td>
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<td>0.005</td>
<td>0.005</td>
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<tr>
<td>P75</td>
<td>0.009</td>
<td>0.014</td>
<td>0.019</td>
<td>0.027</td>
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### Panel B: Correlation

<table>
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<tr>
<th></th>
<th>ED2</th>
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<th>ED8</th>
<th>1st PC</th>
<th>S&amp;P Return</th>
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</thead>
<tbody>
<tr>
<td>ED2</td>
<td>1.000</td>
<td>0.905</td>
<td>0.866</td>
<td>0.772</td>
<td>-0.874</td>
<td>-0.738</td>
</tr>
<tr>
<td>ED4</td>
<td>0.905</td>
<td>1.000</td>
<td>0.986</td>
<td>0.917</td>
<td>-0.982</td>
<td>-0.725</td>
</tr>
<tr>
<td>ED6</td>
<td>0.866</td>
<td>0.986</td>
<td>1.000</td>
<td>0.957</td>
<td>-0.995</td>
<td>-0.720</td>
</tr>
<tr>
<td>ED8</td>
<td>0.772</td>
<td>0.917</td>
<td>0.957</td>
<td>1.000</td>
<td>-0.974</td>
<td>-0.735</td>
</tr>
<tr>
<td>1st PC</td>
<td>-0.874</td>
<td>-0.982</td>
<td>-0.995</td>
<td>-0.974</td>
<td>1.000</td>
<td>0.749</td>
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<tr>
<td>S&amp;P Return</td>
<td>-0.738</td>
<td>-0.725</td>
<td>-0.720</td>
<td>-0.735</td>
<td>0.749</td>
<td>1.000</td>
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Table III
Eurodollar Returns around FOMC Announcements With and Without Press Conferences

This table presents the average absolute returns in Eurodollars one minute before to two minutes after FOMC announcements on FOMC with and without press conferences (PC). ED2, ED4, ED6, and ED8 corresponds to Eurodollar futures at the different quarterly horizon. 1st Comp. is the first component of a principal component analysis among the four Eurodollar returns. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.

<table>
<thead>
<tr>
<th></th>
<th>Mean (PC)</th>
<th>Mean (Non-PC)</th>
<th>Diff. in mean</th>
<th>T-stat</th>
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<tbody>
<tr>
<td>ED2</td>
<td>0.024</td>
<td>0.010</td>
<td>0.013</td>
<td>2.619</td>
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<tr>
<td>ED4</td>
<td>0.037</td>
<td>0.015</td>
<td>0.021</td>
<td>2.861</td>
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<tr>
<td>ED6</td>
<td>0.043</td>
<td>0.018</td>
<td>0.025</td>
<td>2.988</td>
</tr>
<tr>
<td>ED8</td>
<td>0.051</td>
<td>0.020</td>
<td>0.031</td>
<td>3.371</td>
</tr>
<tr>
<td>1st Comp.</td>
<td>0.079</td>
<td>0.032</td>
<td>0.047</td>
<td>3.238</td>
</tr>
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</table>
Table IV
Regression of Monetary News Shock on Equity Returns

This table reports coefficients from regressions of S&P 500 returns on Eurodollar returns. Returns are calculated using prices one minute before to two minutes after FOMC announcements. ED2, ED4, ED6, and ED8 stand for Eurodollar contracts expiring in 2, 4, 6, and 8 quarters. 1st Comp. correspond to the first principal component from using all four Eurodollar contracts. In Panel A, the equity returns are calculated using the e-mini futures contract and in Panel B the equity returns are calculated using the SPY ETF. Asterisks denote statistical significance at the 5-percent level. The standard errors are robust to heteroskedasticity. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.

<table>
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<tr>
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<tbody>
<tr>
<td><strong>Panel A: e-mini returns</strong></td>
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<td></td>
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<tr>
<td>ED2</td>
<td>-0.081***</td>
<td></td>
<td></td>
<td></td>
<td>-0.070***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
<td></td>
<td></td>
<td></td>
<td>(0.026)</td>
<td></td>
</tr>
<tr>
<td>ED4</td>
<td>-0.053***</td>
<td></td>
<td></td>
<td></td>
<td>-0.020</td>
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<tr>
<td></td>
<td>(0.007)</td>
<td></td>
<td></td>
<td></td>
<td>(0.064)</td>
<td></td>
</tr>
<tr>
<td>ED6</td>
<td>-0.046***</td>
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<td></td>
<td></td>
<td>0.071</td>
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<td></td>
<td>(0.006)</td>
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<td></td>
<td></td>
<td>(0.066)</td>
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</tr>
<tr>
<td>ED8</td>
<td>-0.041***</td>
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<td></td>
<td></td>
<td>-0.059***</td>
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<tr>
<td></td>
<td>(0.006)</td>
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<td></td>
<td></td>
<td>(0.023)</td>
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</tr>
<tr>
<td>1st PC</td>
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<tr>
<td>Adj-R2</td>
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<td>0.52</td>
<td>0.52</td>
<td>0.54</td>
<td>0.63</td>
<td>0.56</td>
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<table>
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<tbody>
<tr>
<td><strong>Panel B: SPY returns</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ED2</td>
<td>-0.079***</td>
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<td></td>
<td></td>
<td>-0.065***</td>
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</tr>
<tr>
<td></td>
<td>(0.010)</td>
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<td></td>
<td>(0.025)</td>
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<tr>
<td>ED4</td>
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<tr>
<td></td>
<td>(0.007)</td>
<td></td>
<td></td>
<td></td>
<td>(0.063)</td>
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</tr>
<tr>
<td>ED6</td>
<td>-0.045***</td>
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<tr>
<td></td>
<td>(0.006)</td>
<td></td>
<td></td>
<td></td>
<td>(0.066)</td>
<td></td>
</tr>
<tr>
<td>ED8</td>
<td>-0.040***</td>
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<td></td>
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<tr>
<td></td>
<td>(0.006)</td>
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<td></td>
<td>(0.022)</td>
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</tr>
<tr>
<td>1st PC</td>
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</tr>
<tr>
<td></td>
<td>(0.004)</td>
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</tr>
<tr>
<td>Adj-R2</td>
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<td>0.53</td>
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</table>
This table reports coefficients from regressions of S&P 500 returns on FOMC announcement surprises (ED) and order imbalance (OI) at every two-minute intervals following FOMC announcements, for a total of ten intervals. Panel A shows the regression results of returns on ED. Panel B shows the regression results of returns on OI and Panel C shows the regression results of returns on both ED and OI. The returns in the first interval are calculated using prices one minute before to two minutes after FOMC announcements. ED correspond to the first principal component from using four Eurodollar contract returns expiring in 2, 4, 6, and 8 quarters. OI is the log difference between the number of buys and the number of sells in trade volume units. The equity returns and OI are calculated using the SPY ETF prices and trade volume. Asterisks denote statistical significance at the 5-percent level. The standard errors are robust to heteroskedasticity. The sample period is April 2011 to September 2017. We exclude the FOMC meeting of August 9, 2011.

**Panel A:** \[ R_t = \alpha + \beta ED_t + \epsilon_t \]

<table>
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<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED_t</td>
<td>0.026*</td>
<td>-0.001</td>
<td>-0.002</td>
<td>0.001</td>
<td>-0.002</td>
<td>0.005*</td>
<td>-0.000</td>
<td>0.001</td>
<td>-0.000</td>
<td>-0.001</td>
</tr>
<tr>
<td>R^2</td>
<td>0.55</td>
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<td>-0.01</td>
<td>-0.01</td>
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<td>0.07</td>
<td>-0.02</td>
<td>-0.01</td>
<td>-0.02</td>
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</tr>
</tbody>
</table>

**Panel B:** \[ R_t = \alpha + \beta OI_t + \epsilon_t \]

<table>
<thead>
<tr>
<th></th>
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<th>7</th>
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<th>9</th>
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</tr>
</thead>
<tbody>
<tr>
<td>OI_t</td>
<td>0.010*</td>
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<td>0.004*</td>
<td>0.003*</td>
<td>0.003*</td>
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<td>R^2</td>
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**Panel C:** \[ R_t = \alpha + \beta ED_t + \gamma OI_t + \epsilon_t \]

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<td>ED_t</td>
<td>0.022*</td>
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<td>-0.002</td>
<td>0.001</td>
<td>-0.002</td>
<td>0.004</td>
<td>0.000</td>
<td>0.001</td>
<td>-0.001</td>
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</tr>
<tr>
<td>OI_t</td>
<td>0.005*</td>
<td>0.007*</td>
<td>0.004*</td>
<td>0.003*</td>
<td>0.003*</td>
<td>0.004*</td>
<td>0.003*</td>
<td>0.003*</td>
<td>0.002*</td>
<td>0.002*</td>
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<tr>
<td>R^2</td>
<td>0.60</td>
<td>0.19</td>
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<td>0.23</td>
<td>0.13</td>
<td>0.34</td>
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</table>
Table V  
Regression of Monetary News Shock and Order Imbalance on Equity Returns  
(cont.)

Panel D:

\[ r_{i,t} = \alpha + \beta ED_{i,t} + \gamma_0 OI_{i,t}^N + \gamma_1 OI_{i,t} + \gamma_2 TV_{i,t} + \gamma_3 OI_{i,t} \times TV_{i,t} + \gamma_4 OI_{i,t-1}^N + \gamma_5 OI_{i,t-1}^N \times TV_{i,t-1} + \epsilon_{i,t} \]

<table>
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<tr>
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<tbody>
<tr>
<td>ED_{i,t}</td>
<td>0.021*</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.001</td>
<td>-0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>-0.001</td>
<td>-0.001</td>
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<tr>
<td>OI_{t}^N</td>
<td>0.002</td>
<td>0.001</td>
<td>-0.005</td>
<td>0.001</td>
<td>-0.000</td>
<td>-0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>-0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>OI_{t}</td>
<td>0.008</td>
<td>0.018*</td>
<td>0.039*</td>
<td>0.003</td>
<td>0.023*</td>
<td>0.024*</td>
<td>0.010*</td>
<td>0.014</td>
<td>0.015</td>
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</tr>
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<td>TV_{i,t}</td>
<td>-0.000</td>
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<td>-0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>-0.000</td>
<td>0.000</td>
<td>-0.001</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
<tr>
<td>OI_{t} \times TV_{t}</td>
<td>-0.002</td>
<td>-0.005</td>
<td>-0.032*</td>
<td>0.006</td>
<td>-0.018</td>
<td>-0.015*</td>
<td>-0.001</td>
<td>-0.003</td>
<td>-0.004</td>
<td>-0.010</td>
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<tr>
<td>OI_{t-1}</td>
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<td>-0.003</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.000</td>
<td>-0.002*</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.001*</td>
<td>-0.001</td>
</tr>
<tr>
<td>OI_{t-1}^N \times TV_{t-1}</td>
<td>0.032</td>
<td>0.000</td>
<td>-0.003</td>
<td>-0.004</td>
<td>-0.006*</td>
<td>0.017</td>
<td>-0.006*</td>
<td>-0.001</td>
<td>-0.015*</td>
<td>0.003</td>
</tr>
</tbody>
</table>

| R²       | 0.59 | 0.31 | 0.26 | 0.43 | 0.36 | 0.54 | 0.63 | 0.46 | 0.40 | 0.45 |
Appendix

A. Assessing the Quality of Timestamps

To assess the quality of these timestamps, we retrieve all FOMC announcement timestamps starting with the June 2004 meeting and compare them with timestamps obtained from three different sources: the papers by Bernile, Hu, and Tang (2016) (BHT) and Ozdagli and Weber (2016). BHT and OW use minute precision timestamps from the earliest news article found on Factiva about each announcement. The data from BHT spans the September 1997 to June 2013 meetings while that from OW spans the February 1994 to December 2008 meetings. Their timestamps differ on 43 of their 91 overlapping observations, mostly in the early sample. Since TRTH timestamps have millisecond precision, we classify as good matches timestamps that fall within the same minute as the other data sources. When comparing with BHT, our timestamps differ on 11 out of 72 observations (15%), while they differ with OW on only 4 out of 37 observations (11%). Most importantly, they differ with both BHT and OW on only two observations, with the largest time difference on those days of 2.35 seconds.

B. Additional Figures
Figure A1. Trade Volume per Second around FOMC Announcements

This figure shows the average intraday trading volume per second for E-MINI (all maturities, Panel A) and for the SPY consolidated tape (Panel B) around FOMC announcements in event time. Announcements are separated in those with press conferences (blue solid line) and those without (red dashed line), and the average volume over the ten trading days prior to each announcement is also presented (cyan dotted line). The sample period is April 2011 to September 2016. Data are from TRTH.
Figure A2. Realized Volatility around FOMC Announcements

This figure shows the average intraday realized volatility per minute for the shortest maturity E-MINI (Panel A) and for the SPY consolidated tape (Panel B) around FOMC announcements in event time. Realized volatility for each one-minute interval is computed as the square root of the sum of one-second squared returns. Announcements are separated in those with press conferences (solid blue line) and those without (dashed red line). The shaded areas are pointwise 95% confidence bands around the average realized volatility. The sample period is April 2011 to September 2016. Data are from TRTH.