Manipulation in the VIX?

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May 23, 2017

Abstract

At the settlement time of the VIX Volatility Index, volume spikes on S&P 500 Index (SPX) options, but only in out-of-the-money options that are used to calculate the VIX, and more so for options with a higher and discontinuous influence on VIX. We investigate alternative explanations of hedging and coordinated liquidity trading. Tests including those utilizing differences in put and call options, open interest around the settlement, and a similar volatility contract with an entirely different settlement procedure in Europe are inconsistent with these explanations but consistent with market manipulation. Large transient deviations in prices demonstrate the importance of settlement design.

*Helpful comments were received from Hassan Afrouzi, Gurdip Bakshi, Robert Battalio, Shane Corwin, Martijn Cremers, Andres Donangelo, Michael Johannes, Adam Johnson, Andrew Karolyi, Sam Kruger, Gonzalo Maturana, Dmitriy Muravyev, Ehud Ronn, Alessio Saretto, Paul Schultz, Amit Seru, anonymous option traders, and seminar participants at Florida State University Suntrust Beach Conference, SFS Cavalcade Conference, the University of Bristol, University of Notre Dame, University of Texas-Austin, University of Texas-San Antonio, and University of Warwick. Integra FEC and REC LLC purchased data and provided research assistant support for the project. Griffin is an owner of Integra FEC and Integra REC, both of which engage in financial consulting on a variety of issues. We thank Chirag Agrawal, Tianjiao Zhu, and especially Tin Dinh for excellent research assistance. Griffin can be reached at john.griffin@utexas.edu, and Shams at shams@utexas.edu.

Fair and accurate market prices are fundamental building blocks for efficient capital markets. Yet, market participants have substantial incentives to manipulate these very same financial prices on which our economic system relies. Fortunately, market manipulation is quite difficult. First, if prices move away from fundamentals, other traders have an economic incentive to trade against such deviations. Second, even if a trader successfully moves the price away from the fundamental value, it will generally revert back as the trader exits his or her position. Third, even if a manipulator can impact a security's price and profit from the manipulation, the expected benefit must be greater than the expected penalty costs [Becker (1968) and Ehrlich (1973)]. Considering these lines of defense, security manipulation should be relatively rare, and this is generally consistent with the evidence in developed markets.[1]

Nevertheless, there has recently been a flurry of ostensible manipulation, most notoriously in LIBOR and FX, but also allegations in gold, silver, and oil.[2] Although the events have attracted much attention in the press, there has been relatively little empirical academic research examining specific features of these markets and the mechanisms that allow for manipulation. One commonly proposed solution to avoid manipulation is to use benchmark prices set in the open market. As part of the committee to examine a new LIBOR benchmarking process, Duffie and Stein (2015) embrace the use of open market prices, yet they also note that this may not fully eliminate the potential for manipulation. We examine such a market in which the benchmark is set through market prices. Following research by Kumar and Seppi (1992) and Spatt (2014), we focus on a market with features that might leave it open to manipulation: multiple connected markets with different price-order elasticities, cash settlement, and a finite window to manipulate. The VIX setting is one

[1] Aggarwal and Wu (2006) examine the history of the U.S. SEC manipulation cases from 1990 to 2001 and find that most occur in small and illiquid stocks. Until recently, the extent of alleged manipulation in the press and court cases seems paltry compared to the total trading activity in bonds, equities, foreign exchange, futures, options, and other derivatives. Manipulation in emerging markets may be more common. For example, Khwaja and Mian (2005) document that around half of market maker profits in Pakistan arise from manipulative 'pump and dump' activities.

[2] Libor manipulation was first reported by Mollenkamp and Whitehouse (2008) and later examined by Abrantes-Metz, Kraten, Metz, and Seow (2012) and Gandhi, Golez, Jackwerth, and Plazzi (2015). Vaughan and Finch (2013) report a government investigation of FX manipulation. Denina and Harvey (2014) report allegations of manipulation in gold, Benoit (2010) in silver, and Gosden (2013) and Milhench (2013) in oil.

with two markets with different liquidities and transactions costs: SPX options market with large bid-ask spreads that make it difficult to arbitrage away price deviations, and large and liquid VIX derivative market tied to it that translates such deviations into a sizable potential payoff. Throughout the paper we refer to the SPX contracts as 'lower-level' contracts because they are the base level option contracts that serve as inputs for calculating the value of the VIX, through which the 'upper-level' VIX futures and options values are ultimately determined at the settlement.[3]

The Chicago Board Options Exchange (CBOE) Volatility Index (VIX) is a widely tracked index that gauges the 30-day implied volatility of the market, often referred to as a market 'fear-gauge'. Anderson, Bondarenko, and Gonzalez-Perez (2015) demonstrate that the VIX index can exhibit deviations from true volatility due to the inclusion criteria of illiquid options. Futures and options on the VIX have a relatively large volume. Every month, a settlement occurs where the value of monthly VIX derivatives is set equal to the VIX value calculated from SPX options. This settlement value is calculated from a wide range of out-of-the-money (OTM) SPX put and call options with various exercise prices. A manipulator would need to move the prices of these lower-level OTM SPX options at settlement to influence the value of expiring upper-level VIX derivatives. But, manipulators could leave prints in the data.

Several interesting data patterns emerge. First, at the exact time of monthly VIX settlement, highly statistically and economically significant trading volume spikes occur in the underlying SPX options. Second, the spike occurs only in the OTM SPX options that are included in the VIX settlement calculation and not in the excluded in-the-money (ITM) SPX options. Third, there is no spike in volume for the similar S&P 100 Index (OEX) or SPDR S&P 500 ETF (SPY) options that are unconnected to volatility index derivatives. Fourth, if traders sought to manipulate the VIX settlement, they would want to move the prices by optimally spreading their trades across the SPX strikes and increasing the number

[3] The connection and timing between contracts are shown graphically in Internet Appendix Figure IA.1.

of trades in the deep OTM put options consistent with the VIX formula. Trading volume at settlement follows this pattern, whereas normally deep OTM options are rarely traded. Fifth, there are certain options that have discontinuously higher weight in the VIX formula but are otherwise very similar to other options. These options exhibit jumps in trading volume at settlement that are not present at normal times.

We explore the alternative explanations of pent-up liquidity demand and hedging for these patterns. The increase in trading volume of normally illiquid deep OTM put options could be driven by pent-up demand for these options, where higher liquidity is possibly created by the special settlement as a coordination device. However, OTM call options are also included in the special settlement procedure, but empirical tests show that OTM calls see lower, not higher volume at settlement as they become more OTM. This is inconsistent with the pent-up liquidity hypothesis but consistent with traders strategically following the VIX settlement formula which gives deeper OTM calls less weight. An alternative version of the liquidity hypothesis is that pre-settlement liquidity may instead be positively correlated with trading demand at settlement. However, this alternative is inconsistent with the inverse relation between pre-settlement liquidity and settlement volume for put options. Moreover, the volume spikes around the discontinuous weight thresholds documented previously are inconsistent with liquidity explanations, since pre-settlement liquidity of the options are continuous around the threshold.

To further investigate the liquidity and manipulation hypotheses, we gather data from the European volatility index, the VSTOXX, which is similar in nature to the VIX but has a different settlement procedure with only options at €0.5 and above being included in the calculation. This design puts a very high weight on the option with €0.5, because small changes in price can exclude or include the option from settlement calculation. Interestingly, the trade volume per minute for options at €0.5 increases to around 130 times of that in the rest of the day, whereas the options below this threshold experience minimal trading activity. Additionally, the VSTOXX index is calculated every five seconds, and the settlement is calculated as the average of the index values between 11:30 a.m. and 12:00 p.m. A trader trying to absorb liquidity would trade when the options with the best quotes became available, but a manipulator would want to trade every five seconds to optimally influence the index calculation. We find that trades cluster consistently exactly at five-second intervals throughout the settlement period, whereas the thirty-minute windows before and after exhibit no such patterns. Overall, the findings are all consistent with the liquidity of options at settlement being generated by those who wish to strategically trade the exact VIX or VSTOXX formula at the exact time intervals that the indices are calculated.

We next examine two possible hedging explanations. First, we examine a trader with hedging motives who, at some point prior to settlement, simultaneously opens a futures contract in the upper-level VIX derivatives and hedges that position through underlying SPX options. When the futures expire, the investor unwinds his position and liquidates the SPX options. However, the data exhibits no such pattern in either open interest or trading volume of SPX options prior to settlement. For the deep OTM put options, open interest jumps more than fourfold, indicating that traders are opening new contracts and not closing out previous positions.

The second hedging alternative is that upon expiration of VIX derivatives, investors desire to roll their hedging positions into SPX options in a manner that exactly replicates the VIX weighting formula. However, inconsistent with a sudden demand for such a specific SPX position, we find no volume jump on the VIX settlement day for other tightly related exchange-traded products that mimic the same payoff. Additionally, for four interspersed months in our sample where there are no expiring VIX derivatives on normal settlement days, we find no evidence of greater underlying SPX trading either at or prior to the settlement time, which is inconsistent with VIX investors transferring their VIX demand to SPX options. Finally, for the VSTOXX, settlement prices are set with average prices from 11:30 a.m. to 12:00 p.m. CET, but futures positions expire at 12:00 p.m.[4] Manipulators should push

[4]The settlement value of VSTOXX options is also calculated using the average VSTOXX values between 11:30 a.m. and 12:00 p.m. CET, but the options can be exercised on the settlement day until 21:00 CET.

prices beginning at 11:30 a.m., whereas for hedgers, 12:00 p.m. is the relevant time to roll the positions over. We see the trade volume on options used in VSTOXX calculation spikes promptly at 11:30 a.m. on settlement days and persists only up until 12:00 p.m., with trades clustering at five-second intervals as discussed before. The trading activity also leads to large movements in the value of VSTOXX index during the 30-minute settlement window that cannot be explained by movements in the underlying index. Overall, these aggregate patterns seem inconsistent with rollover hedging, though we expect that there are some hedging trades also present in the data.

We examine price deviations of individual SPX options and the aggregate VIX at settlement using multiple benchmarks. When comparing the VIX value at settlement to a VIX value computed from the mid-quotes of the SPX options right after the settlement, where both are calculated from the same range of options included in both the settlement and the open, the two diverge by an average of 31 basis points, or 1.5% of the VIX settlement value.[5] The distortionary costs of settlement deviations to exchange-traded VIX derivatives are approximately $1.81 billion. We examine price deviations at settlement of seven other CBOE volatility indices with similar processes and commonly find deviations of more than five percent for these small indices, highlighting the robustness and generalizability of the findings. In terms of the mechanics of the VIX price movement process, prices appear to be moved by aggressive incremental orders in the pre-open period prior to settlement.[6]

Overall, we find considerable interesting activity in index options around VIX settlement. The most natural explanation for these patterns appears to be attempted manipulation. However, we cannot rule out other possibilities. Although we find that the dollar distortions in the VIX derivatives are sizeable, Spatt (2014) argues that the real economic costs of manipulation are typically considerably larger than their direct costs; distorting market

[5]The VIX deviations are considerably larger if benchmarked using adjusted option quotes from the night before, in a systematic way that suggests the use of open prices are likely understating the deviation.

[6]These results are consistent with findings in Cao, Ghysels, and Hatheway (2000) and Biais, Hillion, and Spatt (1999) that orders are able to move prices prior to market openings even in settings where there is no commitment to trade.

prices undermines trust, hinders trade, and reduces liquidity in financial markets. We hope to see academic research scrutinize other markets for potential gaming and to see more effort on robust market design[7] and monitoring.

1. Related Literature, VIX Overview, and VIX Derivatives Characteristics

This section briefly outlines the related literature and security features that have been shown to lead to potential manipulation. We then examine the security design of the VIX and whether the market exhibits these features.

1.1 Related Literature and Characteristics for Potential Manipulation

There is a small but growing empirical literature on potential market manipulation.[8] Also considerable theoretical research has examined characteristics of markets that may be conducive to manipulation [e.g., Jarrow (1992), Allen and Gale (1992)]. Kumar and Seppi (1992) and Spatt (2014) describe cross-market manipulation and identify different price-order elasticities across markets, cash settlement, and a finite period to manipulate as main facilitators. First, when there are multiple markets with different price elasticities, manipulation is more feasible than in a single market. Because of different market liquidities, it may be feasible for a manipulator to move the price of an illiquid lower-level contract that a larger upper-level contract is tied to.

Second, manipulation is difficult for an asset with physical settlement. Suppose a manipulator pushes the price of a lower-level asset up. Nonetheless, when physical delivery of the asset takes place, the manipulator will take possession of an asset at an inflated price,

[7] Anderson, Bondarenko, and Gonzalez-Perez (2015) develop a more robust measure of implied volatility that empirically outperforms the VIX.

[8] Most strikingly, Christie and Schultz (1994) showed that market makers avoided odd-eights to keep spreads high, and that this activity was collusive. Ni, Pearson, and Poteshman (2005) find that stock prices cluster closer to strike prices on days with option expiration and that this behavior could be consistent with both hedging and stock price manipulation. Golez and Jackwerth (2012) find similar patterns of prices being pulled toward strike prices in S&P 500 futures. Manipulation has been shown in stock prices at quarter-ends by hedge funds (Ben-David et al, 2013) and year-ends by short-sellers (Blocher, Engelberg, and Reed, 2010).

and that asset may quickly fall to the original value when the manipulator tries to exit the position. With cash settlement, a manipulator can deploy more capital in the upper-level asset than the position size that he will take in the lower-level asset.

Third, a finite time period to manipulate prices can make the costs of manipulation smaller. Although an auction may increase liquidity and reduce the incentive to manipulate, it is also open to gaming. Spatt (2014) states: "Although it often has been viewed that a closing or opening auction is less vulnerable to manipulation because of the thickness of the market, the discontinuous transition to the auction does point to vulnerabilities for possible manipulation as illustrated by the potential for manipulating virtual (indicative) prices during the preopening when it is not costly (or is of very limited cost) to artificially alter the price as well as the run-up to the closing auction."

Below, we examine the actual setting of the VIX settlement process and then examine whether the features of the market as identified in the literature above allow for potential manipulation.

1.2 VIX Mechanics

Options on the S&P 500 Index are widely traded at various strike prices and maturities. Using the premium that investors are willing to pay for call and put options at various strike prices, observers can calculate the implied volatility of the market. Because of this interest by market participants, the CBOE formally calculates the VIX in real-time and updates the index every fifteen seconds using SPX options with more than 23 and less than 37 days to expiration.[9] An overview of the details of the VIX calculation is provided below and described in more detail by the CBOE VIX White Paper (2015). To accommodate trading demand from hedgers and speculators, the CBOE launched VIX futures on March 26, 2004

[9]Before October 6, 2014 the VIX index did not use weekly options and was calculated using nearby and second nearby monthly options with at least eight days to maturity. When the nearby options were less than eight days to maturity, the calculation involved extrapolation using the two nearest monthly option series with more than 30 days to maturities. The change in calculation does not affect our analysis because the VIX settlement value is always calculated from the single monthly option series that is exactly 30 days to maturity.

and VIX options on February 24, 2006.[10]

The settlement of VIX options and futures typically occurs on the third or fourth Wednesday of each month. The exercise-settlement value of VIX futures and options is calculated using the auction clearing prices of SPX options in an auction called the Special Opening Quotation (SOQ). To be included in the settlement auction, orders can be submitted and canceled by market participants and market makers prior to market open. Starting at 7:30 a.m. CST, given the orders submitted up to each point in time, best bid and ask and indicative prices for each option can be seen by market participants. Between 8:15 a.m. and 8:30 a.m., strategy orders, which are SPX option orders that are related to positions in VIX derivatives and span over a wide range of strikes with 30 days to maturity, can no longer be submitted or canceled. Only orders unrelated to outstanding VIX positions, including those submitted by liquidity providers, can be submitted after 8:15 a.m. At 8:30 a.m. CST, the CBOE executes SPX options orders at market-clearing prices and removes all remaining unexecuted orders.

The SPX options' auction clearing prices are used in the VIX formula to calculate the VIX settlement value at that point in time.[11] Importantly, the SPX options series used in the VIX settlement calculations are ones that expire in exactly 30 days (normally on the third Friday of the next month). The timing of the VIX settlement and the SPX option settlement is illustrated in Internet Appendix Figure IA.2. ITM options are not included in the settlement value. All the OTM options are included in the settlement calculation as long as the option is not a zero-bid option. An option is considered zero-bid if there is no remaining bid on the option after the settlement trades are cleared. Moreover, the tails of the option chain on both the put and call sides are cut when two consecutive zero-bid

[10]ETNs and ETFs (such as tickers VXX, TVIX, UVXY, XIV) also invest long or short in VIX futures and options, but to our knowledge, are not typically holding expiring VIX futures and options at settlement if they employ the most common strategy of shifting money from the front month to the next month futures as the VIX approaches maturity. Bakshi, Madan, and Panayotov (2015) note that trading volatility products has grown rapidly, and VIX options are second most active only to SPX options.

[11]In practice, more than 99.9% of options are set at the trade price. Yet, prices for non-traded options that meet the inclusion criteria are set at the midpoint of the bid-ask spread.

options are observed; all the deeper out-of-the-money options are excluded.[12]

1.3 Do the VIX Derivatives Have Characteristics that Make Manipulation Possible?

Below we examine specific features of the VIX in relation to Section 1.1, which discussed facilitating factors for manipulation. First, the upper-level VIX market is large and liquid, enabling a trader to invest a sizeable position in VIX derivatives. In contrast, many of the lower-level SPX options, where the VIX values are derived from, are illiquid. Anderson, Bondarenko, and Gonzalez-Perez (2015) show that the fluctuations from inclusions of these illiquid OTM options can lead to unnecessary variation in the VIX value. In fact, the day prior to the settlement, deep OTM options rarely trade. Even trading a small number of contracts can potentially move these options prices. Moreover, the large bid-ask spread of the deep OTM options allows for large price changes inside the spread that are therefore immune to arbitrage. Nevertheless, the time of coordinated trading at the settlement auction may attract trading that increases the liquidity of tail options and hopefully mitigates this issue.

Second, the VIX derivatives are cash settled. Therefore, if the VIX settlement value deviates from its true value, the VIX position will automatically be cashed out at the deviated price.

Third, the settlement occurs within a short period of time based on the SPX options pre-open auction. Large buy or sell orders for the OTM SPX options in the SOQ auction can affect the VIX settlement value by changing the options' auction-clearing price through the demand-supply equilibrium. This means there is a finite time period where the costs of manipulation must be incurred. While not all three conditions may be simultaneously needed for manipulation, the occurrence of all three potentially provides a ripe setting for

[12] If a large buy order causes a would-be zero-bid option to have a positive bid, then the option will be included in the settlement calculation. It is also possible for an aggressive sell order that consumes all bids greater than zero to drive the best bid price to zero. The upward pressure to include an option in the tails might be more common because writing deep OTM put options involves large margin requirements while buying the options does not. Santa-Clara and Saretto (2009) show that this feature has a large impact on the capacity to write OTM puts, especially when investors write the options more aggressively.

profitable manipulation.

2. Data and Testable Predictions

2.1 Data

Data are obtained from Tick Data, Bloomberg, the CBOE, OptionMetrics, and Deutsche Börse Group. The datasets contain lower-level SPX options as well as upper-level VIX futures and options. Nevertheless, most of this report's attention focuses on lower-level SPX options, as this is where a potential manipulator would need to trade. The period of examination is from January 2008 to April 2015, though much of our results focus on more recent periods. For the SPX options, we use Tick Data intraday quote and trade data with millisecond granularity for a three-day window around each settlement day from January 2008 to April 2015. Four months of intraday data from January to April 2015 are collected from Bloomberg to crosscheck data accuracy. We use OptionMetrics to analyze daily patterns for SPX, OEX, and SPY options. It contains daily variables such as trade volume and open interest. Moreover, to capture the exact trades included in settlement calculation, we use monthly settlement reports and settlement imbalance reports issued by CBOE.

For upper-level VIX derivatives, VIX options data are from OptionMetrics, and VIX futures data are from the CBOE Historical Market Data, from January 2008 to April 2015. Also, data on exchange-traded variance swaps (also called variance futures) are from CBOE, covering the time period from December 2012 to August 2015. Historical daily and intraday data on VIX and other volatility indices such as those on Crude Oil, Gold, Emerging Markets, Brazil, NASDAQ-100, Russell 2000, and short-term S&P 500 are from Bloomberg. The intraday data on the volatility indices are only available recently from October 2014 to April 2015. Finally, data on disseminated VSTOXX index and EURO STOXX 50 options that are used to calculate the VSTOXX are from Deutsche Börse Group, and data on disseminated EURO STOXX 50 index are from Bloomberg.

2.2 *Overview of Testable Predictions*

The basic steps that a manipulator needs to take include:[13] 1) opening long positions in the VIX derivatives prior to settlement, 2) submitting aggressive buy orders in the SPX options during the settlement auction, and thereby causing the auction-clearing prices of SPX options, and as a result, VIX settlement price to rise, and 3) obtaining the higher price for the upper-level futures or options when they settle. Note that while the example shows an upward manipulation, a trader could also manipulate the VIX downward by trading in the reverse fashion.

Trading in an attempt to manipulate the VIX settlement should leave patterns in the data that can be examined. First, volume spikes in the SPX options will be examined at the VIX settlement. Second, this activity will be compared to: a) non-settlement times, b) OEX options for the S&P 100, and c) SPY options for SPDR S&P 500 ETF that do not have tradable upper-level derivatives. Third, SPX options volume will be compared between SPX OTM options that are included in the VIX settlement and ITM options that are not included.

VIX is calculated based on the following formula:

$$VIX = 100 * \sqrt{\frac{2}{T}\sum_i \frac{\Delta K_i}{K_i^2} e^{RT} Q(K_i) - \frac{1}{T}\left[\frac{F}{K_0} - 1\right]^2}$$

where T is time to expiration, R is the risk-free interest rate, K_i is the strike price for the ith OTM option, $Q(K_i)$ is the price of that option, ΔK_i is the average distance between the strike price of the ith OTM option and the strike prices above and below option i, F is the forward index level, and K_0 is the first strike price below the forward index level. Given that only OTM options are included, options with $K_i > K_0$ are calls, those with $K_i < K_0$ are puts, and for $K_i = K_0$ both calls and puts are included, each receiving half the weight.

Note that the strike price K_i in the VIX formula above is squared and in the denominator.

[13] These are shown graphically in Figure IA.3.

Hence, as put options become more OTM (i.e. have a lower strike price), VIX becomes more sensitive to their price changes.[14] It can be shown that the manipulator would spread their volume across the options in a manner directly proportional to the sensitivity of VIX to price changes in each option contract (as illustrated in Internet Appendix IA.A). Thus, our fourth point of examination is that volume and relative price deviations should increase as put options become more OTM.

Finally, the VIX formula provides for a direct relationship between the VIX and the variable ΔK_i, which is the average distance between the strike price of the option i and the strike prices of the options immediately above and below option i. For example, many options are separated by only five points from the nearest options on each side. If an OTM put option has a strike of 1395, and the strikes below and above that option are 1390 and 1400 respectively, then the average distance between the surrounding strikes is five index points ((1400 - 1390) $\div$ 2 or $\Delta K = 5$).[15] Next, suppose that below the 1390 option is a put option with a strike of 1375. In this case, the 1390 option would be 15 points away from the nearest strike below and 5 points from the strike above, resulting in an average strike difference of 10 ((1395 - 1375) $\div$ 2 or $\Delta K = 10$). Hence, the option at 1390 will have nearly twice as much weight in the VIX settlement calculation as the very similar option next to it at 1400 or 1395. If a manipulator is planning to influence the price of the VIX, they should be willing to spend twice as much to influence the 1390 option as compared to the option at 1400 or 1395. The prediction is that trading should increase around the ΔK_i thresholds, where certain options receive a higher weight in the VIX calculation.

[14] The effect of the strike price is the opposite for call options after controlling for ΔK measure: the deeper OTM a call option, the higher its strike price and lower its weight in VIX calculation. This is shown in Internet Appendix Table IA.1 where we control for ΔK and in Figure IA.4 where we show the sensitivity and volume only for call options with $\Delta K = 5$. To avoid unnecessary complexities and confusion, we report most of the results only for put options here, which also have a higher weight in VIX calculations. The equivalent results for the calls are reported in the Internet Appendix.

[15] This is shown in Internet Appendix Figure IA.5 for a put option.

3. Volume Patterns at Settlement

This section will test the predictions outlined in the previous section.

3.1 Volume Spikes

Panel A of Figure 1 shows average daily volume across all SPX options. Typically, volume is low and increases as options approach expiration. However, here the volume spikes thirty days prior to expiration. This is not due to any kind of obvious S&P 500 market-related event, but it is the date that the VIX settles.

Panel B removes the SPX volume that trades exactly at the settlement of the VIX, thirty days before SPX expires. The volume for the rest of the day shows that the pronounced spike is not present aside from settlement trades, implying that the spike is driven by the settlement volume.

To examine the possibility that some other event besides the VIX settlement causes volume to spike, the volume of SPX options is compared to OEX and SPY options. The S&P 100 and 500 track each other very closely. Additionally, there is an OEX volatility index (VXO) that is calculated from OEX options and that closely tracks the VIX index. Nevertheless, there are no tradable futures or options on the VXO and hence no incentive to manipulate the index. Moreover, the SPY ETF tracks the S&P 500 index and has the same fundamentals, but there is no volatility index calculated using SPY options. Panel B plots the average volume on the OEX and SPY. The OEX and SPY volumes exhibit no major movement thirty days prior to maturity.

The VIX formula only uses OTM options. Panel C of Figure 1 shows that the volume spike is entirely driven by the OTM options, and there is no increase in volume for ITM options. Table 1 confirms this result in the regression of the form:

$$Volume_{it} = \beta_0 + \beta_1 SettlementDay_t + \beta_2 OTM_{it} + \beta_3 SettlementDay_t * OTM_{it} + \alpha_t + \epsilon_{it}$$

where $SettlementDay_t$ is a dummy variable that takes the value of one if the day is a VIX settlement day, and zero otherwise, OTM_{it} is a dummy variable equal to one if option i at settlement time t is out-of-the-money and equal to zero if in-the-money, and α_t is the SPX options expiration date fixed effect. Throughout the paper, we use the expiration date fixed effect when possible to control for variations in volume and other characteristics of options across different expiration dates and focus on the cross-section of different strike prices within expiration dates.

The Table shows that a) the increase in volume on the settlement day is entirely in OTM options (Settlement Day times OTM) and not in ITM options, which is the benchmark; b) the increase is economically very large; and c) it is statistically significant with a t-statistic of 11.86. These results are consistent with SPX trading being driven by the VIX settlement.

3.2 VIX Sensitivity and Option Volumes

Panel A of Figure 2 shows how sensitive the VIX is to price changes of individual put options. This sensitivity measure is calculated for each strike, as the basis point change in VIX as a result of a $0.05 change in that specific option's price, while keeping prices the same for all other strikes.[16] As discussed above, someone wishing to manipulate the index should submit increasing volume as sensitivity increases. Panel B of Figure 2 shows put options' volume across strike price ranges at the settlement and shows that volume increases as the put options become more OTM, which is consistent with the sensitivity patterns shown in Panel A.[17]

Table 2 examines these patterns for both puts and calls combined in an OLS regression framework with standard errors clustered by date. Volume does increase with VIX sensitivity, and the relationship is highly statistically significant. Additionally, this relationship is

[16] To compute the marginal effect of SPX options price changes on the VIX, we use the $0.05 increment because that is the minimum tick size of the option prices. The fact that $0.05 change is a large price effect for low price deep OTM options does not affect the results here because we examine the costs and benefits caused by the absolute price changes in the option prices, not the relative changes.

[17] Similar patterns using alternative bins of moneyness for put options are shown in Internet Appendix Figure IA.6.

economically significant, with over half of the variation in settlement volume explained by the VIX sensitivity measure and the date fixed effects.

Panel C of Figure 2 shows that the positive relationship between VIX sensitivity and volume is only confined to the settlement. Indeed, on the day before, the day after, and the rest of the settlement day, put options with higher VIX sensitivity trade significantly less.[18]

3.3 Discontinuity in VIX Sensitivity

The last prediction outlined in Section 2.2 is that trading volume should 1) spike on the higher ΔK options if someone is attempting to trade according to the VIX formula, and 2) not jump if the trading is unrelated to VIX. In the option chains used in settlement calculations, we flag the strikes where two adjacent options have different ΔK; we call it a "jump" in ΔK and denote the two adjacent strikes around the jump as high and low ΔK. Next, we sort the strike prices above and below each jump relative to the strike prices right at the jump. In Figure 3, for each jump, characteristics of the put options around the jump are normalized relative to the high ΔK option (which has a given value of 1) and then averaged across different jumps.[19] Panel A of Figure 3 plots the sensitivity of the put options around the thresholds. Higher ΔK translates into a higher VIX sensitivity and, by construction, there is a jump in the sensitivity of the options around the threshold. We ask whether trading volume exhibits a similar jump as might occur from a strategic manipulator.

Panel B shows a large jump in trading volume right at the threshold for put options. The differences between the two are highly significant.[20] Note that other features of the options, such as the strike price and moneyness do not exhibit a jump around the threshold

[18]Similar patterns for call options are shown in Internet Appendix Figure IA.7.

[19]For instance, the option labeled zero on the x-axis of the graph represents the high ΔK put option, for which all the characteristics are normalized to 1. The point ten units to the left represents the tenth strike price below the high ΔK option. For puts, the jump in ΔK normally occurs when one moves to an option with a lower strike. VIX sensitivity, trade volume, strike price, and moneyness for the option contracts around the jumps are normalized relative to the high ΔK option and then averaged across different jumps.

[20]Table IA.2 formalizes the test for the trade volume around the jump. A t-test shows large difference in settlement volume for strikes around the jump in Panel A. Panel B reports the results of an instrumental variable regression of volume on VIX sensitivity using the jump as an instrument for the sensitivity, which verifies the significant difference in settlement volume around the jump.

(as shown in Figure IA.8). In other words, these options around the threshold are nearly identical except for their greater weights in the VIX calculation.[21] It could be argued that the volume on options with a wider gap between the strike prices above and below should be normally larger, as they cover a wider range of demand for adjacent missing strike prices. Both Panels A and B of Table IA.2 show that volume does not jump with ΔK at non-settlement times.

3.4 Evidence Overview

Overall, this section has shown the existence of a volume spike that only occurs at the time of the VIX settlement. The patterns are only present in SPX options and not in nearly identical OEX or SPY options, and only in OTM SPX options that are included in the VIX settlement calculation and not in ITM options that are excluded. VIX exhibits an increasing sensitivity to the price of put options that are deeper OTM and, consistent with this relationship, there is a strong and statistically significant increase in volume as put options become more OTM, but only at the settlement. Finally, VIX is more sensitive to contracts that are further apart from other options, and accordingly, these contracts exhibit an economically large and statistically significant jump in volume on settlement that mirrors their importance in the VIX formula. In sum, the evidence is consistent with attempted manipulative activity, but there are other potential explanations to examine.

4. Alternative Explanations

There are three main alternative explanations for the observed patterns in the data. First, the settlement is a period of coordinated liquidity trading. Because deep OTM SPX options are infrequently traded and have low liquidity, traders could be concentrating their trading around the settlement auction to take advantage of the higher liquidity of the options at that point. Second, hedgers could take out positions in the underlying SPX options prior to

[21] Internet Appendix Figure IA.9. reports similar patterns for call options.

settlement to hedge their VIX derivative position and then close out their position when the VIX derivatives settle. Third, hedgers could be rolling over their VIX derivative positions to underlying SPX options when they expire. We investigate these explanations below.

4.1 Trading Illiquid Options at the Liquid Settlement Time

Deep OTM options are normally very illiquid and costly to trade because of high bid-ask spreads. We posit that the VIX settlement auction, in conjunction with a belief that other traders participate in the auction, provides an opportunity for those who have pent-up demand to trade deep OTM options. Thus, the patterns of increasing volume for deep OTM options may just be a result of the settlement being used as a coordination device. We provide multiple tests here that help disentangle the liquidity and manipulation explanations.

First, if the settlement auction is a period of coordinated liquidity for all options, the liquidity hypothesis predicts higher volume for deep OTM options. This includes the illiquid deep OTM call options as well as deep OTM puts.[22] However, while the manipulation hypothesis has the same prediction for put options, it predicts less volume at settlement for normally illiquid deep OTM calls, because as call options become more OTM (and thus less liquid), they receive a lower weight in VIX calculation. Therefore, we can disentangle the two hypotheses by testing the relationship between non-settlement liquidity and settlement trade volume across the strikes of the call options: liquidity trading predicts a negative relationship and manipulation predicts a positive relationship. We proxy for liquidity in non-settlement times by using the average of prior 30-day volume as well as the average of prior 30-day inverse percentage bid-ask spread. Table 3 columns 1 and 2 report that the settlement volume of call options is positively correlated with the two liquidity measures, or that less liquid calls actually trade less at settlement. This relationship is inconsistent with the liquidity hypothesis that predicts more settlement trading in the less liquid options, but consistent with the manipulation hypothesis because the deep OTM call options actually

[22] Table IA.3 reports a positive relationship between moneyness and the liquidity at pre-settlement times for both OTM put and call options.

have lower weight in VIX calculations than less OTM options. Columns 3 and 4 verify that, as predicted by both hypotheses, less liquid, deeper OTM put options have a higher volume at settlement.

Second, to further separate the two hypotheses for the put options, we can regress their settlement volume on the two liquidity measures above and the VIX sensitivity measure derived in Section 3.2 to see which one has a stronger effect. Columns 5 and 6 of Table 3 show such results. When including the VIX sensitivity measure and the liquidity measures in the same regressions, the liquidity measures lose their explanatory power. Non-settlement trade volume becomes marginally significant with a t-statistic of 2.16 and non-settlement percentage spread becomes insignificant with a t-statistic of 1.79. In both specifications, the VIX sensitivity measure is highly statistically and economically significant with t-statistics of 3.33 and 3.19, respectively. These findings suggest that the volume at settlement is primarily driven based on the VIX formula. Additionally, in Figure 2, Panel B, there is almost no trading in ITM options at settlement, even though they are also part of the SOQ; since the difference is that their prices are not included in the VIX settlement, this is also more consistent with manipulation hypothesis.

An alternative version of the liquidity hypothesis is that the liquidity of options before settlement is a leading indicator for demand during the settlement. This hypothesis would suggest that options that trade more in pre-settlement period are also expected to trade more at settlement. However, this alternative liquidity hypothesis would be inconsistent with the volume of the OTM put options, which see an increase in trading at settlement as options become more OTM, despite little pre-settlement trading. This alternative explanation would also be inconsistent with near the money ITM options which see high trade volume at other times, but almost none at settlement. Hence, a uniform liquidity hypothesis cannot explain the fact that at settlement, illiquid OTM puts trade more while illiquid OTM calls trade less.

Third, Internet Appendix Figures IA.10 and IA.11 show the volume across strike prices for all non-settlement days in the sample, divided into aggregate volume quantiles. Even in the top 5% days in terms of aggregate volume, which have a very similar daily volume as the settlement days, the options trade in the opposite pattern as the settlement trades. This suggests that if there is pent-up demand for illiquid SPX options, it is not leading to trading on other days of high trading activity.

Fourth, it is worth returning to the discontinuities examined previously in Section 3.3. The pent-up liquidity hypothesis predicts that volume in illiquid options should increase at settlement, but there is no reason why volume should experience large jumps around certain thresholds, unless they also have discontinuous liquidity at other times. But, both Panels A and B of Table IA.2 show that at normal times volume is continuous around the thresholds. Thus, the discontinuities in trading at the settlement cannot simply be explained by coordinated liquidity trading, but are consistent with trading based on the VIX formula.

Fifth, we turn to the European VIX, VSTOXX, which has a very similar structure to the U.S. VIX, but has important features in the settlement calculation that differ from VIX. The European VIX excludes options with prices less than €0.5 from the VSTOXX calculation. The manipulation hypothesis predicts that traders who want to manipulate the prices would not trade deep OTM options that are far below the €0.5 cutoff; the €0.5 cutoff is critical for a trader who wishes to affect the settlement.[23] The liquidity hypothesis predicts trading in deep OTM puts close to expiration because this is a time of coordinated trading for illiquid options; the €0.5 cutoff is not a critical threshold for coordinated liquidity trading. Figure 4, Panel A, shows the trade volume of EURO STOXX put options that are used to calculate VSTOXX, sorted relative to the €0.5 cutoff, and averaged across settlement dates. Those options on the left side of the vertical line have an average trade price of less than €0.5 during settlement period. First, the volume is particularly high for options near the €0.5 cutoff because those options are very critical to the settlement calculations; they

[23] If there are more than one strike with the price equal to €0.5, only the nearest to the money will be included in the VSTOXX. But if no other strike trades at 0.5 Euro, pushing the €0.4 option up affects the calculation. Moreover, if price of the €0.5 option at cutoff is pushed upward to €0.6, then another strike can be added to the tail at €0.5. This makes the €0.5 option highly critical in VSTOXX settlement.

are at risk of total exclusion or inclusion from calculations due to even small price changes. Second, there is little volume on options that are worth less than €0.5 (and do not affect the VSTOXX calculation).[24] In the U.S. VIX settlements there is no such cutoff. On average, if one compared to the U.S. VIX calculation, 38 put options of less than €0.5 ($0.67 on average over the sample period) have large volume and are included in each U.S. VIX settlement, with an average trade volume of 2111 contracts. Those options account for 52% of the aggregate settlement volume for put options over the entire sample period. Empirically, we see activity in deep OTM options in the U.S. where they have influence on VIX, but almost no activity in Europe where they have no influence on VSTOXX.

Sixth, the VSTOXX settlement is calculated using the average of the normal VSTOXX index over a thirty-minute settlement window. The VSTOXX index is calculated every five seconds. Since there is no special auction procedure for VSTOXX settlement, there is no particular reason why liquidity traders should trade at a set frequency. However, for a manipulator who wants to affect the settlement value, it is optimal to trade every five seconds. To examine this, in Figure 4, Panel B, we divide every five-second interval during the settlement window into fifty buckets of 100 milliseconds (one-tenth of a second) each. Then, in the first five minutes of the settlement we identify the bucket with the highest number of trades and use the time of that bucket to set the clock to zero. We plot the number of trades in 100-millisecond buckets in each minute in the next 25 minutes of the settlement period. The graph shows that the trades are clustered nearly exactly at five-second intervals, meaning that the 100-millisecond bucket in each five-second interval with the highest trading is exactly the same bucket across different five-second intervals. To examine if this type of systematic trading every five seconds is normal, we perform the same exercise in the 30-minute window before and after the settlement. We find no such clustering patterns outside the settlement (Figure IA.13).

Overall, the differences in the volume patterns between puts and calls, ITM and OTM

[24] Figure IA.12 shows the volume over time for options around the cutoff on settlement days.

options, discontinuities within the VIX and VSTOXX calculations, and the differences in volume patterns and timing of trades between the VIX and VSTOXX are most consistent with aggregate trading volume patterns capturing gaming of the respective settlement formulas. Although many features of the aggregate patterns do not support a consistent liquidity trading hypothesis, the settlement likely contains a mix of trading motives, including those seeking liquidity.

4.2 Unwinding Previous Hedging Positions

When investors open a position on VIX derivatives, they may hedge those positions by trading in SPX options. Right at the settlement time, because VIX derivatives expire, investors may unwind SPX hedging positions, leading to the abnormal trading patterns. The trader could accept that a static hedge will not replicate the VIX perfectly because of market moves, yet sit on the two positions until VIX future maturity. Then, at VIX settlement, the VIX positions expire and the trader simultaneously unwinds his SPX trades. This rough hedge could explain the volume spike.

To examine this possibility, we look at two tests. First, if someone takes positions in options prior to expiration and then unloads his or her SPX positions when the VIX settles, there should be sizeable open interest and volume in the options before the settlement. Panel A of Internet Appendix Figure IA.14 shows that the open interest of deep OTM put options prior to settlement is minimal, indicating that there is seemingly little hedging activity in listed SPX options prior to the settlement. Moreover, the large increase in open interest at settlement indicates that most of the activity is due to opening new positions.[25]

Second, we examine the options that are right at the threshold of being ITM or OTM. It is nearly impossible for a trader to know exactly which options will be included in settlement when he opens the hedging positions in SPX options a couple of weeks (or even a couple of

[25] Panel B of Figure IA.14 shows that the total volume of deep OTM puts in the prior 30 days is well below the volume on the settlement day, again indicating that traders are not simply liquidating hedging positions at the settlement even for a static hedging portfolio of SPX options. Figure IA.15 shows similar results for call options.

days) prior to settlement.[26] When settlement time comes, the trader will have some options that were OTM in the past but now are ITM and therefore not included in the VIX. The trader should still unwind these positions at settlement because they no longer have the need to hedge. Therefore, we should see volume spikes for both barely OTM and barely ITM options. We find that for the options that are clearly ITM, there is almost no trading at the VIX settlement.[27] This is again inconsistent with the hypothesis that the trading is driven by a hedger who unwinds the hedge position opened before the settlement.

4.3 Replacing VIX Derivatives with SPX Options

The second hedging hypothesis is that at exactly the same time that the upper-level VIX derivatives expire, traders replace them with SPX options through an order designed using the VIX weighting formula. This trade would replicate a variance swap contract and hence we will refer to it as a synthetic variance swap. The question is whether the motivation of the trade is to hedge or to influence VIX settlement, and we provide three tests to disentangle the two hypotheses.

First, we look to the four months in our sample without VIX derivative contracts in the market. This goes back to 2005 when VIX futures were relatively new. If option traders had a need to hedge short-run volatility using SPX options, then we would expect to observe large amounts of SPX options trading that replicates the variance swap in the months with no VIX futures. We first compare the volume in the settlement period between months with and without VIX futures. Panel A of Table IA.4 shows that even though months with and without VIX futures do not have a significantly different volume for ITM put options at normal settlement times, the trade volume of OTM put options is significantly higher

[26] The average daily volatility of the S&P 500 over the last five years is 0.99%. With an SPX level around 2,000, this corresponds to a 19.8 points movement per day in index value of the SPX. With most at-the-money option chains five points apart, this means that three option contracts cannot be determined to be in either OTM or ITM even a day prior to expiration. At one week intervals, the average volatility would be roughly 2.61, which translates to 52.2 points or 10 contracts that may or may not be included in the settlement.

[27] These results are displayed in Figure IA.16.

for months with expiring futures.[28] Additionally, Table IA.4, Panel B, shows that the open interest of OTM put options before settlement is very similar between the months with and without VIX futures. This indicates that in months without near-term VIX futures, there is no strong demand for replicating short-term variance swaps, which is inconsistent with the hedging explanation but consistent with either lack of a trade coordination device or manipulation incentives associated with the settlement.

Second, we investigate the trade patterns on exchange-traded variance swaps around the settlement times. Variance swaps have long been traded on OTC markets and had started trading on the CBOE as "S&P 500 Variance Futures" in December 2012. Unlike OTC variance swaps, the daily data on trade volume and open interest of the exchange-traded variance swaps are publicly available. If traders tend to replace VIX derivatives at expiration with variance swaps, one would expect to see concentrated trading of exchange-traded variance swaps around the VIX settlement time, but there is no spike in trade volume and open interest of that product on the VIX settlement day (as shown in Internet Appendix Figure IA.18).

Third, differences in the settlement calculation of the VSTOXX provides the opportunity to disentangle the timing of manipulation versus hedging. The last trading time of VSTOXX derivatives and the time contracts settle is at 12:00 p.m. CET. Unlike the U.S., there is no special auction mechanism for the settlement. Instead, the settlement is calculated using a 30-minute average of the disseminated VSTOXX value, computed every five seconds between 11:30 a.m. and 12 p.m. To manipulate the VSTOXX settlement, it is not effective to push the prices right at the expiration, and one needs to push the prices continuously during the 30-minute settlement at five-second calculation intervals as discussed before. Therefore, the manipulation hypothesis predicts that we should observe abnormal activities in VSTOXX market during the entire 30-minute settlement calculation. In contrast, if the purpose is to replace the expiring upper-level derivatives with lower-level options at expiration, the

[28] These results are also shown graphically in Internet Appendix Figure IA.17.

activities should concentrate at 12 p.m. when the positions expire. For coordinated liquidity purposes, this might also be the time to trade as hedgers roll over their positions. If a trader wished to exit an upper-level VSTOXX position earlier, it could be done at any point in the data, and there is certainly nothing special about 11:30 a.m.

Figure 5 Panel A shows that the trade volume of EURO STOXX 50 options jumps right at 11:30 a.m. and stays high until 12 p.m. This only occurs for OTM options and there is not much activity in ITM options that are not used in the settlement. Moreover, to examine whether these trades affect the value of the VSTOXX index, Panel B of Figure 5 shows the absolute five-second percentage changes of the VSTOXX index, averaged over five-minute intervals for settlements between January 2014 and August 2015. The changes significantly increase exactly at 11:30 a.m. To test whether these movements are caused by market movements, we estimate a five-minute rolling regression of VSTOXX values on EURO STOXX 50 index, which is highly negatively correlated with VSTOXX. We then estimate the prediction error of the next VSTOXX observation. Figure 5 Panel C shows that the prediction error significantly increases right at 11:30 a.m., indicating that the higher changes in VSTOXX are disconnected from market movements. Table 4 presents these results more formally. The absolute percentage changes and the prediction errors are significantly larger during the entire 30-minute time period of settlement calculation.[29] We also do not see a volume spike at 12 p.m., which would be consistent with traders rolling over their positions when they expire.

In sum, there is nothing special about 11:30 a.m. for hedgers since their positions expire at 12 p.m. The fact that these abnormal patterns do not spike at 12 p.m. is inconsistent with both hedging hypotheses, but the elevation at 11:30 a.m. strongly supports the manipulation hypothesis. Additionally, the clustering of trades every five seconds and the jump in trading

[29] Additionally, in the Internet Appendix Figure IA.19, as an example of an actual settlement with suspicious swings, we report the most recent settlement in our data, August 2015. Here the VIX went up at 11:30 a.m. by 63 basis points and stayed up until 12 p.m., but fell back down to within 4 basis points of the starting point by 12:05 a.m. Over this time the STOXX index experienced only a small upward move. Other deviation patterns are typically not as large as this settlement, but price volatility consistently sharply elevates at 11:30 a.m.

around the €0.5 threshold discussed before are also inconsistent with both hedging explanations. Overall, our tests indicate that liquidity and hedging hypotheses are not complete explanations for the patterns that we see in the data, though we expect that the aggregate activities contain a mix of coordinated liquidity, hedging, and manipulative trading.

5. Prices, Costs, and Mechanics of Manipulation

This section examines whether traders are successful in moving prices and if the distortionary costs in the VIX derivative market are sizable, whether the costs of pushing prices are justified by its benefits, whether the price deviations could be arbitraged away, and finally what the mechanics of the pre-open activity are that cause the price deviations.

5.1 Are Traders Successful in Moving the Prices?

We now ask if prices move at the settlement, and by how much. We examine the price movements for individual SPX options, how that translates into deviations in the aggregate VIX, and how the effect is spread across different options.

5.1.1 Price Movements in Individual SPX Options

We examine potential price deviations in individual SPX options by comparing the prices of SPX options at settlement with their first observable price after the market opens (typically between 8:30 a.m. and 8:31 a.m.), as well as prices at the close of the day before. We adjust the open prices of SPX options for movement of the underlying index and the time decay between the settlement to the open, and previous close prices for movement of the underlying index, time decay, and overnight changes in volatility, proxied by changes in the second-term VIX futures.[30] To examine the patterns separately for settlements with positive and negative price pressure on the VIX, we first measure deviations of the aggregate VIX settlement relative to the VIX values right after the market opens. To examine upward and

[30] The procedures are detailed in Internet Appendix IA.B.

downward price pressure separately, we divide the sample into settlements with large positive deviations (more than +20bp) and large negative deviations (less than -20bp) relative to the open benchmark.

To examine the settlement prices relative to the bid-ask spread after the settlement, we sort options into bins based on their bid-ask spread right after the market opens[31] and then pool them across settlement days. Panel A of Figure 6 reports the settlement prices of the put options relative to the spread at the open, where the size of the bubbles is proportional to the number of observations at each price. For days with large positive deviations, most prices are above the mid-point, and generally cluster slightly below or close to the ask price. Some observations are even above the ask price. For example, for the SPX options with bid-ask spread of 50 cents after the open, most settlement prices are close to the ask, but some go up to 90 cents above the mid-quote. A similar pattern holds across different bid-ask spreads. The prices cluster close to the bid in days with large negative deviations.

Given that the settlements are sorted into positive and negative deviations based on the deviation of the VIX settlement relative to the VIX right after the open, we examine an alternative benchmark for individual SPX options that is not affected by the way VIX deviations are defined. Thus, we compare the individual SPX options settlement prices relative to the option quotes at the close of the previous day (while sorting the settlement days relative to the open). As shown in Panel B, this yields very similar patterns: In days with positive (negative) deviation of the VIX settlement relative to the open, SPX option prices cluster near the ask (bid) of the previous close.

Table IA.5 reports the paired t-test of the individual SPX put option prices at settlement compared to the quotes at the market open and the previous close. Panel A shows that in days with positive deviations, settlement prices are significantly 18 cents above the mid quotes and 38 cents above the bid, while they are pushed all the way towards the ask prices.

[31] For options with missing quotes or quotes that are strictly inferior to other strikes in the same option series, we use quotes of options that strictly dominate that option, i.e. the best ask of the more ITM options or the best bid of the more OTM options.

In days with negative deviation, prices are 18 cents below the mid-quotes and 34 cents below the ask, but not statistically different from the bid. Panel B finds similar results when option prices are compared to the previous close.

We formally test whether price changes at settlement are a transitory effect. Table IA.6 estimates a regression of the price changes from settlement to market open on the changes from the previous close to the settlement. The prices here are adjusted for the index movement, time decay, and volatility changes as explained before. The reported R-squared shows that 74% (57%) of the price changes of individual options from settlement to open for put (call) options can be explained by the changes from the previous close to the settlement. This result confirms that the price deviation is indeed a transitory effect related to the orders submitted at the settlement. The overall results in this section suggest that SPX option prices at settlement systematically deviate from the mid-quote of the previous close across the strike prices and then revert back towards the mid-quote after the settlement.

5.1.2 Deviations in the Aggregate VIX

To gauge how movements in SPX options prices translate into aggregate deviations of the VIX, we compare the VIX index calculated from the SPX options prices at settlement to the VIX index calculated from the mid-quote of the SPX options right after the market open.[32] To control for deviations that could be caused by including different range of strikes at settlement and at the benchmark, we conservatively use the exact same range of non-zero bid options included in both the settlement and the open. We call this the open benchmark. Figure 7, Panel A, shows the deviations in the VIX from January 2008 to April 2015. The deviations can be either positive or negative,[33] and the average absolute value of the deviations is 31 basis points per settlement day. The deviations appear largest in late 2010 and in 2011, and are generally smallest in 2014.

[32] There is on average a 25 second difference between the settlement and the prices used here.

[33] The average raw deviation is -0.5 basis points and the median is 2.5 basis points. Of the absolute deviations of more than 20 basis points, 57% of the deviations are positive and 43% are negative.

We also benchmark for an objective value of the VIX at settlement using three alternative measures, all calculated from the same range of individual SPX options included in the settlement and the open: 1) a VIX index computed using the raw mid-quotes of the previous close and then adjusted by adding the overnight changes in the second-term VIX futures, 2) a synthetic VIX using the value of OTM options implied from the mid-quotes of ITM options through put-call parity, and 3) a VIX index computed from the adjusted mid-quotes of the SPX options at the previous close, adjusted for changes in market conditions as discussed in section 5.1.1.[34] All of the benchmarks use the same range of non-zero bid options included in both the settlement and the open right after the settlement.

Table IA.7, Panel A, shows that the deviations from the open benchmark and the other measures are highly correlated with estimates ranging from 0.74 to 0.79, and all significant at the 0.001 level. During the sample period from May 2010 in which all benchmarks are available, the average absolute deviation is 27bp relative to the open benchmark, 61bp relative to the previous close (adjusted for changes in second-term VIX futures), 34bp relative to the ITM benchmark, and 57bp relative to the index calculated from the adjusted quotes of individual SPX options at the previous close.

The open benchmark may underestimate the deviations if it contains a spillover of price and quote changes from the settlement. This seems to be the case. We find that on days with positive deviations of settlement relative to open, the deviations of settlement relative to previous close are even significantly more positive, and on days with negative deviations of settlement relative to open, deviations from previous close are even significantly more negative.[35] Nevertheless, we still use the open benchmark as the main reference to define the deviations and market distortions in the paper because it is the most conservative and conceptually simplest benchmark for the VIX settlement values given that it is computed

[34] Construction of the benchmarks 2) and 3) requires information from the settlement imbalance reports, which limits the sample period for those benchmarks to after May 2010. The details of calculations are explained in the Internet Appendix IA.C.

[35] Panel B of Table IA.7 reports this using a paired t-test of the difference between deviations from open and previous close for the full sample where both the open benchmark and the previous close benchmark are available.

less than 30 seconds after the settlement.

5.1.3 The Source of Deviations

We now examine the sources of the aggregate VIX deviations across different SPX options strike prices. For each settlement, we divide the sample of put options into three subgroups with equal number of strikes based on their moneyness: 1) Close-in OTM Puts, 2) Deeper OTM Puts, and 3) Very Deep OTM Puts. We examine call options as a separate group. The put option subgroups contain 31-32 strikes on average at each settlement and the call group contains 36 strikes. The VIX deviation caused by each group is calculated by aggregating the deviation caused by each individual option in that subgroup settled at the actual settlement price, while holding the price of the other options the same as the benchmark. We do this both using prices at open and the adjusted prices at the previous close. In days with large positive deviations, 29% of the deviations are caused by close-in OTM puts, 22% from deeper OTM puts, 22% from very deep OTM puts, and 28% from the calls. The numbers are 44%, 24%, 10%, and 23% for negative days (as reported in Table IA.8, Panel A).[36] Although the volume is much higher in deeper OTM put options, the prices are much smaller, which is why close-in-OTM options still carry relatively more weight in the total deviation. Overall, if one calculates the basis points of VIX deviation per money overpaid in the SPX option market relative to the benchmarks, each group of options gives similar deviation per dollar overpaid, as shown in rows four and five of both panels. This is because in general the trade volume is spread across strike prices increasing for the smaller-priced put options, consistent with the optimal trading strategy shown in the Internet Appendix IA.A.

[36] It should be noted that to control for the range of options included in the settlement and the benchmark, we use the exact same non-zero bid options included in both the settlement and open benchmark calculation and ignore the tail-extension or tail-cutting effect that causes deviation in the very deep OTM options. The numbers relative to the previous close are comparable, as reported in Panel B.

5.2 *Are the Market Distortions Sizable?*

The market distortion caused by the settlement deviations can be calculated by multiplying the difference between the settlement and the open benchmark by the open interest of the VIX derivatives at settlement.[37] This measure reflects the deviation of the settlement prices of the SPX options from the mid-quotes right after the market opens. This calculation is made on both VIX futures and ITM VIX options for each settlement date. Panel B of Figure 7 plots the monthly dollar distortions of futures and options. The distortionary costs vary widely across settlements, and more of the costs are born on the VIX options.

The distortions are the largest in 2011, 2012, and 2013 respectively, and they are not caused by 2008 market events when the VIX reached historic high. As reported in Internet Appendix Table IA.9, across the sample period of January 2008 to April 2015, the distortionary costs to the upper-level futures and options were $1.81 billion.[38] Our deviations are also overly-conservative because deviations are measured only for individual SPX options that are included in the VIX both at the settlement and at the open. If we include the tail-effect (more in Section 5.5) by allowing the settlement and benchmark have their actual range of options included in the VIX, the distortion is $1.95 billion. These findings highlight a sizeable wealth transfer taking place from the investors on one side of trades in the VIX derivatives to the other.

Interestingly, the VIX is not the only volatility index with a similar settlement design. Crude oil, iShares MSCI emerging markets ETF, Russell 2000, iShares MSCI Brazil ETF, NASDAQ 100, short-term S&P 500, and gold all had volatility indices with tradable upper-level futures or options until most of them were recently suspended.[39] Panel C of Figure

[37] The open benchmark is calculated using the mid-quotes of the exact range of SPX options included in both settlement and right after the open. Only if the required SPX series do not open in the data right after the market opens, we use the officially disseminated VIX at open as the benchmark, which only happens in five settlement days.

[38] The average distortionary cost is $21 million per settlement. Moreover, our calculations do not include OTC positions and hence may be understated. Additionally, recall that the deviations here use the open-benchmark, which as noted earlier, was the most conservative of benchmark methods.

[39] The contracts for crude oil, gold, and Brazil ETFs were discontinued after May 2015, the contracts for short-term S&P 500 and NASDAQ 100 after June 2015, and the contracts for the emerging markets ETF

7 plots the deviations at settlement and shows that magnitudes are commonly over 5% deviations. Because the volume in the upper-level contracts is thin, the total distortion in all contracts only amounts to $11.34 million dollars (as calculated in Table IA.10). The settlement deviations in other indices indicate the generalizability of these findings and the need to consider a better settlement design.

5.3 Do Deviations Provide Arbitrage Opportunities?

Do the settlement deviations lead to potential arbitrage profits to those trading against the deviation? For example, suppose that the true value of a deep OTM put option is $0.15. Now someone at settlement pushes the price up to $0.25. This creates an arbitrage profit if someone can sell the option at $0.25 and buy back at a price close to $0.15.

However, OTM SPX options usually have a high bid-ask spread outside of the settlement and even more so for the illiquid deep OTM puts, which VIX is more sensitive to. In the example above, if the bid and ask prices of the option are $0.05 and $0.25, there would be no arbitrage opportunity because the arbitrageur must buy back the option at $0.25.

The CBOE reports VIX indices that are calculated from SPX options' bid prices (VIXB) and ask prices (VIXA). Table 5 Panel A reports the summary statistics for the spread between VIXB and VIXA at the open on settlement days over the period from January 2008 to July 2015. The average spread is an economically large 1.55 VIX units, which translates into 6.8% of the midpoint. As long as the deviations are within the spread, it is not the case that someone can immediately arbitrage away the deviations. Indeed, the fact that the spread of the SPX options is large outside of the settlement means that the VIX deviations can be large; the large spread leaves open the possibility for large deviations that are immune to price correction. Nevertheless, given the time difference between the settlement and the benchmarks, we find that 14% of the SPX options settlement prices fall outside of the adjusted spread at open benchmark and 27% outside the adjusted spread at

after July 2015.

previous close, as previously shown in Figure 6.

5.4 Is the Cost of Pushing Prices in the SPX Justified by Its Benefits?

If there was a single market where a manipulator had to both push the prices and collect the payoffs in that market, the manipulation would not be profitable, especially with the high spread present in the SPX options market. However, here a manipulator can push the prices of illiquid SPX options, but reap the payoffs in the liquid VIX derivatives market. Table 5 Panel B reports that the percentage bid-ask spread for VIX futures over the sample period is around 0.3%, which is far less than the 6.8% spread between VIXB and VIXA calculated from the spreads on the underlying SPX options.

For the manipulation to be profitable, the profit made on the VIX derivatives should be larger than the costs of trading and pushing prices of the SPX options. We compare the total size of the exchange-traded VIX derivatives market at settlement relative to settlement trades in SPX options in terms of their Vega exposure, which shows how much the value of each market would shift as a result of change in volatility, as measured by VIX. For example, suppose that a trader has a long position in VIX futures and wants to push the settlement value up by buying SPX options at an inflated price in the pattern that mimics VIX weights. If the Vega of his portfolio in VIX future markets is equal the total Vega traded in SPX options at settlement, he receives a $1 payoff in VIX future market from inflating VIX settlement, but this costs him $1 on purchasing overpriced SPX options. However, if the size of his VIX futures Vega is twice the size of traded SPX options, every dollar spent to move the settlement would leave him with $1, or a 100% profit.

We examine the relative sizes of the markets over the sample period in Table 5 Panel C. The size of VIX futures with open interest at settlement is on average 5.7 times the size SPX options traded at settlement, and it is 7.3 times for VIX options that are in-the-money at settlement and are affected by settlement value. Together, the upper-level market is 13 times the SPX trades at settlement in terms of Vega exposure, which indicates that manipulation in the lower-level would be feasible for a trader that holds a sizable fraction of the upper-level market.

Another consideration here is the transaction costs paid by traders to unwind the SPX options they take at settlement. Traders can offset their exposure using other exchange-traded or OTC products such as OTC variance swaps after the settlement, they might be partially offsetting exposure to certain option Greeks opened at some point before the settlement, or they might directly unwind the exact SPX options after the settlement. Our data only allows us to track the last possibility. Figure IA.20 Panel A shows that the open interest of deep OTM put options increases right at settlement and does not decrease afterwards, and Panel B shows that trade volume is minimal for deep OTM puts after the settlement. Thus, traders do not seem to unwind the exact positions in the SPX option market. More detailed investor-level data is required to examine the possibility of traders using other derivatives or more sophisticated strategies in the SPX market to offset their settlement positions.

5.5 What is the Mechanism through Which Prices are Pushed?

The question remains of how exactly the SPX option prices move. Biais, Hillion, and Spatt (1999) and Cao, Ghysels, and Hatheway (2000) show that pre-open orders can convey substantial information and move prices even in the absence of any firm commitment to trade. Spatt (2014) also emphasizes that manipulators can move these virtual prices in the absence of trading.

To see how these orders affect prices before the settlement, we look at the order imbalance reports on settlement days.[40] The imbalance reports are issued by the CBOE and include information such as bid and ask price, size, imbalance quantity, and last sale price, which is used to calculate the indicative price (of what the market-clearing price would be if the

[40] The imbalance reports with a full range of strike prices start from May 2010. Here we consider positive and negative absolute deviations of at least 20bp, which leaves us a sample of 25 days with positive deviations and nine days with negative deviations.

auction clears at that time).

Figure 8 graphs the movements for the OTM put options' imbalance report indicative prices over time. Panel A shows that, in days with large positive VIX deviations, the average indicative SPX price starts low in the morning and increases from 7:45 a.m. to 8:15 a.m. This is in line with aggressive buy orders moving prices upwards. However, since no VIX related strategy order can be submitted from 8:15 a.m. to 8:30 a.m., prices typically go down after other players including market makers dominate the market, indicating that other traders put in orders to sell the overpriced options and adjust the prices downward. However, the prices are not fully reversed, and we observe more downward adjustment from settlement to open. Note that this last adjustment from settlement to open is what we use to define positive and negative VIX deviations, so the price movements before 8:15 a.m. and between 8:15 a.m. and 8:30 a.m. are not artifacts of how we define positive and negative deviation. In fact, they show how the aggressive orders before 8:15 a.m. still leave a significant effect on the settlement prices at 8:30 a.m., even after prices are partially corrected. Rather than just focusing on the average, Figure 8 Panel B shows the 25%, median, and 75% of the distribution. Note that the pattern of positive movements prior to 8:15 a.m. and a downward price drift from 8:15 a.m. to 8:30 a.m. generally holds.[41]

Table 6 shows the findings more formally. On days with a positive deviation at settlement, we have a significant positive deviation from before 8 a.m. to 8:15 a.m. and then a significant reversal from 8:15 a.m. to 8:30 a.m. As expected, we have a negative adjustment from settlement to market open. The results for days with a negative deviation are marginally significant or not significant, although they have the expected sign.

The aggressive orders can most easily be seen in the bid-ask spread. In a balanced market of buyers and sellers, the price to buy (bid) should never be above the sell (ask). Yet, occasionally 'crossed' markets occur when prices for the best bid exceed the best ask. Cao, Ghysels, and Hatheway (2000) show that crossed markets are more likely in the pre-

[41] Although there are only nine settlement days in the sample with large negative deviations, general patterns are in the opposite direction as shown in Figure IA.21.

open and are indicative of strong information signaling by certain traders.

Ten minutes after the open, the percentage bid-ask spread is positive, as one expects. Yet at pre-open of settlement days, the spread is largely negative, indicating that traders are submitting aggressive buy or sell orders (as shown in Figure IA.22). More interestingly, consistent with the idea that manipulators have no incentive to affect ITM option prices, the spread at settlement is only negative for OTM options and turns positive for ITM options. To the extent that different traders have different positions and some traders are pushing the prices up while others are pushing the prices downward, the manipulation effectiveness is mitigated. Such a fight over the settlement price is also consistent with the elevated volume.

It is interesting to examine whether the magnitude of the deviations across time is related to the time-series of trade volume at settlement. We regress the absolute value of deviations on the Log volume at the settlement. Despite the small sample size of around 80 settlement observations, the settlement volume is positively and significantly (t-statistic=2.42) related to the absolute VIX deviations (as shown in Table IA.11, Panel A). A one unit increase in Log volume results in 13bp more deviations in VIX settlement. This provides confirming evidence that the trading activity is related to the deviations.

In our previous analysis, we measured the deviations caused by non-zero bid options that are included in both settlement and the open. This conservative method is not affected by issues surrounding benchmarking the settlement with illiquid options, but also ignores pushing or cutting the tails. We now examine the relationship between the range of OTM put options included in the settlement calculation and the settlement deviations, where we calculate the deviations using the actual range of options included in settlement relative to the actual range of options trading at the open.[42] Compared to the range of likely options included in the settlement based on the prices the night before, the tail is longer on 53 settlements and shorter on 25 settlements. Panel B of Table IA.11 shows that there is a

[42]This allows for different ranges of options at the settlement and open. The deviation calculated in this manner is five basis points higher than the "open benchmark" calculated with the same range of options both at settlement and at the open that is used throughout the paper.

positive correlation between deviations from open and the length of the tail of put options added to the VIX relative to the previous night.

Overall, the analysis shows that there are aggressive orders to buy or sell prior to the market settlement that do not occur at other times and that they are related to price deviations.

6. Conclusion

We show that not only is it feasible to influence the VIX settlement, but also present price and volume patterns at settlement consistent with what one would expect from such strategic trading. In particular, a volume spike occurs: a) only at the time of the VIX settlement, b) only in the OTM options that are used to calculate the VIX, c) not in similar S&P 100 Index (OEX) or S&P 500 ETF (SPY) options, which do not have a tradable volatility index, d) proportional to the sensitivity of VIX to each strike price, and e) with a jump for options that have a discontinuously higher weight in the VIX calculation, which does not occur at non-settlement times. We thoroughly investigate alternative explanations of coordinated liquidity and two forms of hedging but find that these explanations do not fit the data as well as the manipulation hypothesis. These findings have important implications for settlement design, regulators, enforcement, and investors.

The deviations in the VIX account for an average of 31 basis points of movement in settlement values, which amount to over $1.81 billion dollars in settlement price distortions for the upper-level VIX futures and options from 2008 to April 2015. The large size ($108 billion dollars over our sample period) of VIX futures and options that are exposed to the settlement relative to size of SPX options at settlement, makes manipulation cost-effective for a large trader. Although in other markets these price deviations might create arbitrage possibilities for (and price correction by) those trading against them, we show how the high transaction costs in less liquid SPX options during the non-settlement window make such deviations feasible.

In sum, our findings show that the VIX settlement appears susceptible to manipulation, and that the aggregate evidence aligns itself with what one would expect to see in the case of market manipulation of certain settlements. However, we cannot fully rule out all potential explanations without more granular data.

In thinking through solutions to avoid potential manipulation, a common focal point is often optimal security design. Market design is clearly important, but financial complexity makes it difficult for regulation to keep pace with changing market design, and it is naive to think that policy makers can foresee all possible gaming mechanisms. For example, the VSTOXX settlement procedure seems to be designed with an eye to mitigate the impact of temporary price pressure, but nevertheless also exhibits patterns strongly indicative of gaming the settlement. A concern is that complexity in the derivative market can be used to obfuscate financial deception [Partnoy (2009)]. Policies that encourage transparency in reporting trading activities and even anonymized trader identities can counteract increasing complexity. We hope to see more research analyzing the extent of potential gaming of market prices in other contexts.

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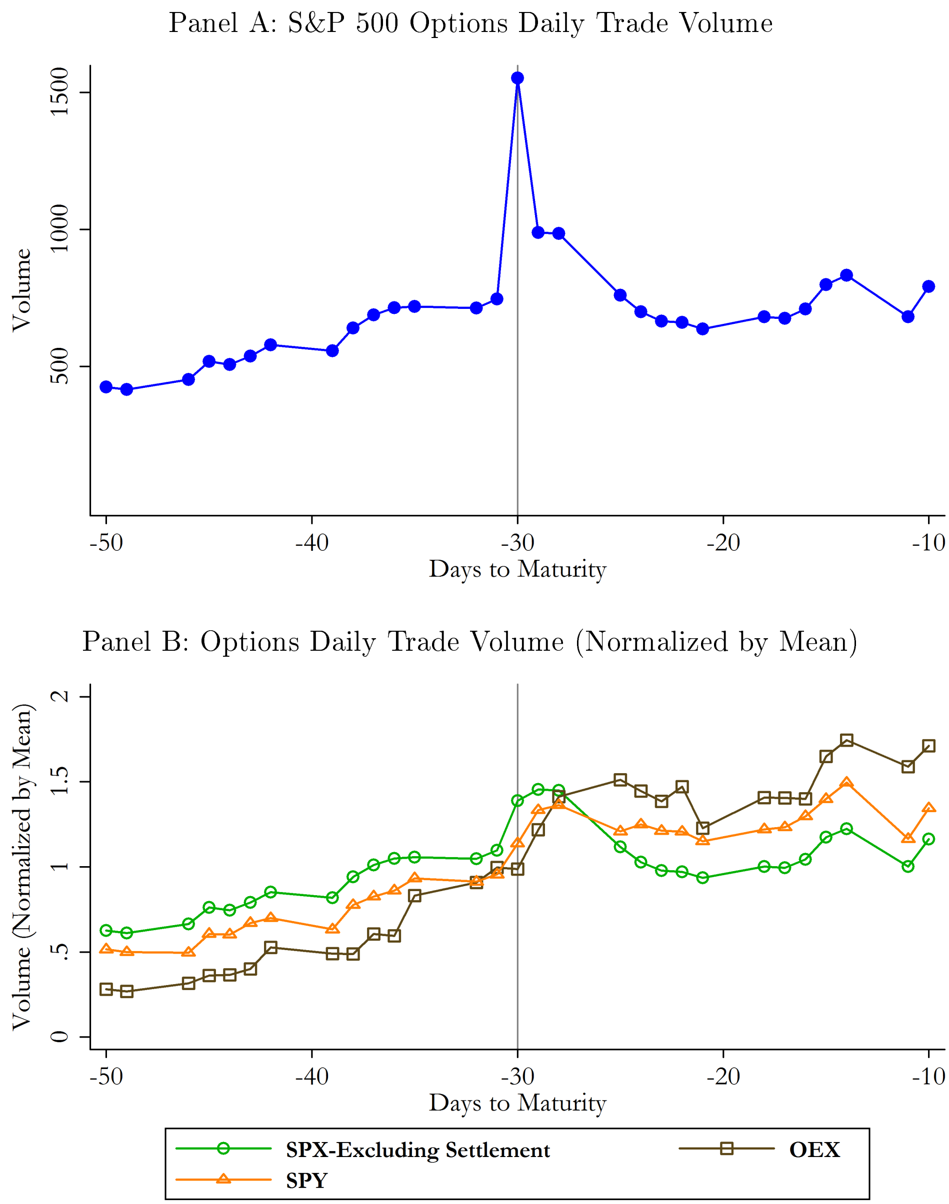
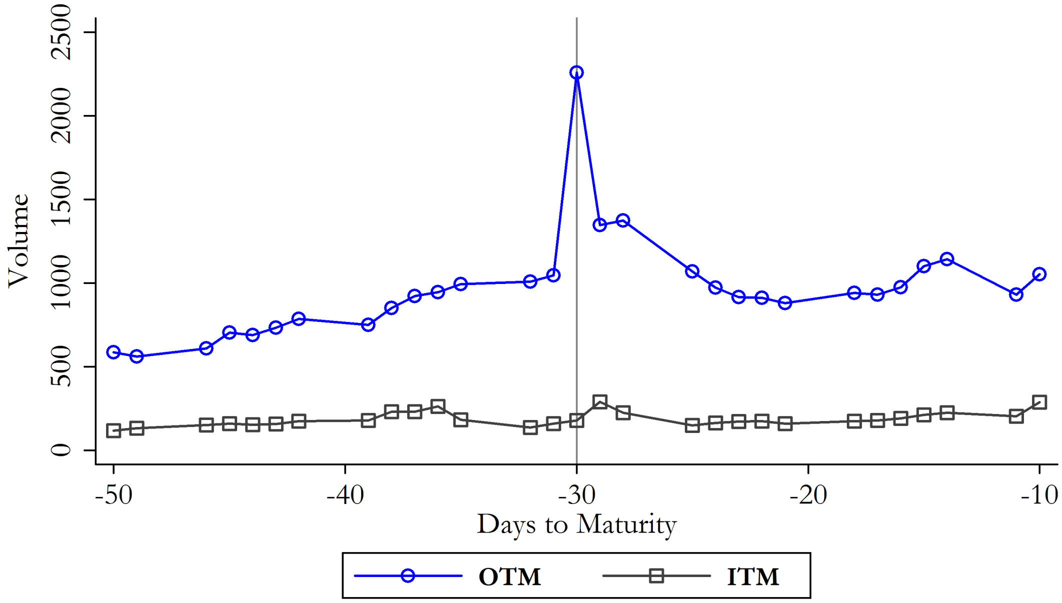


Figure 1. Trade Volume of S&P 500, S&P 100, and SPY Options. This figure shows the average trade volume of monthly S&P 500, S&P 100, and SPY options by days to maturity. The sample consists of the option chains used in VIX settlement calculations from January 2008 to August 2014. Panel A shows the daily trade volume of S&P 500 options averaged across different strike prices and settlement dates. The center vertical line shows 30 days to maturity, which is the settlement day for VIX derivatives. Panel B shows the average daily trade volume calculated in the same way as Panel A for S&P 500 options excluding the trades occurring at the preopening settlement (green circles), S&P 100 options (brown squares), and SPY options (orange triangles). The volume in Panel B is normalized by the average trade volume for each option during the period. Panel C shows the SPX options' trade volume separately for OTM (blue circles) and ITM (gray squares) options.

Panel C: OTM and ITM Options Daily Trade Volume



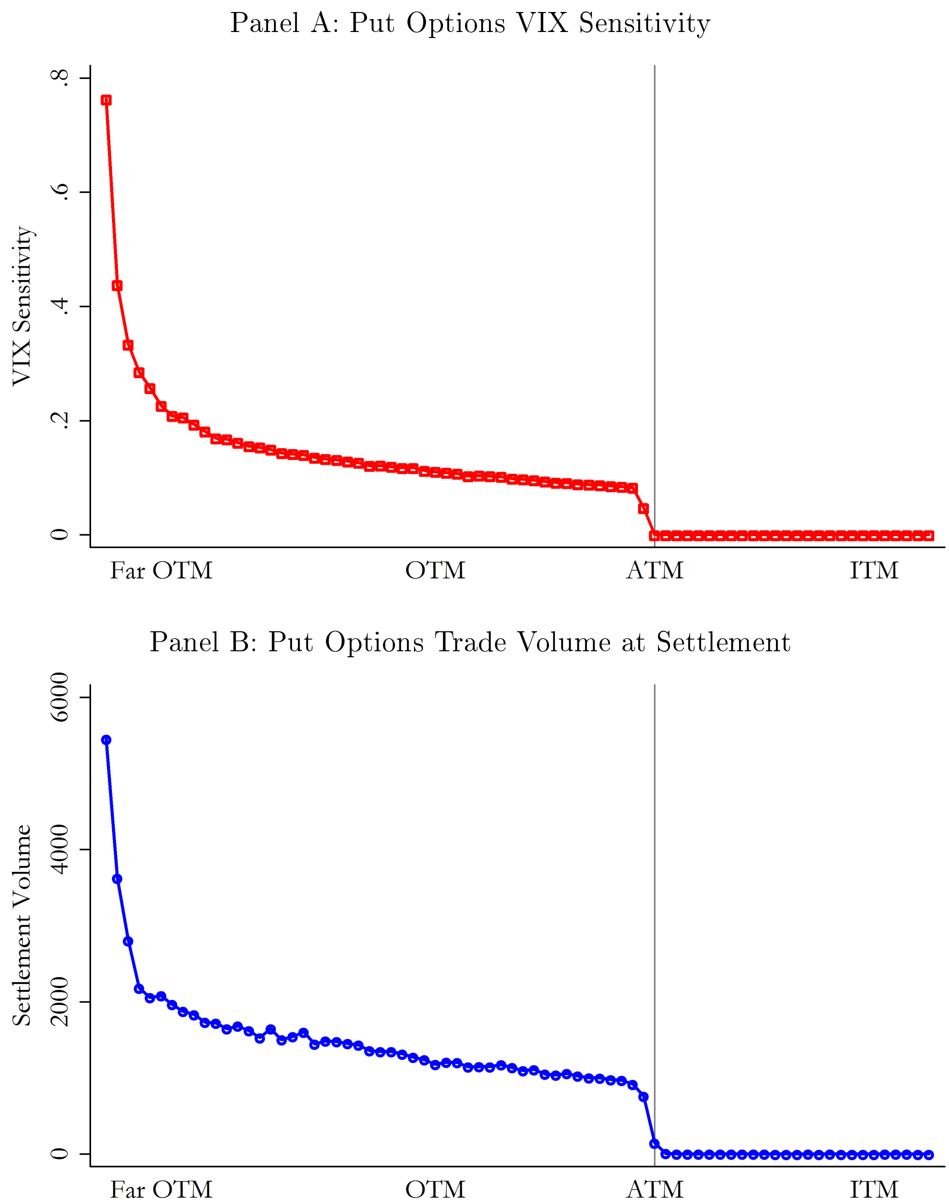
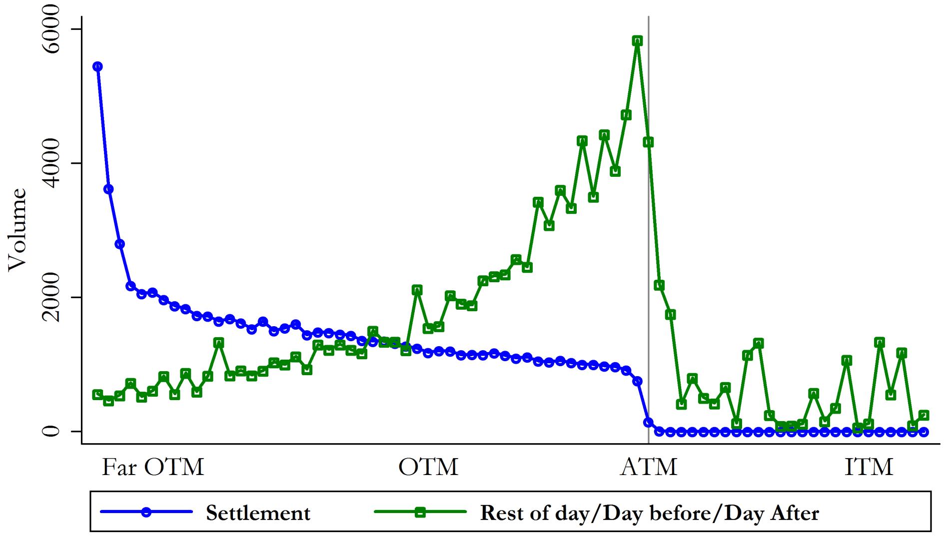


Figure 2. VIX Sensitivity and Trade Volume of Put Options. This figure shows the relationship between trade volume of monthly S&P 500 put options and the sensitivity of VIX settlement value to price movements in those options. The sample consists of the put options used in VIX settlement calculations from January 2008 to April 2015. VIX sensitivity for each option is calculated as the change in VIX settlement value as a result of five-cent price movements in that option, holding all other prices constant. Each month's put options used in settlement calculation are divided into 50 bins based on their moneyness, and the VIX sensitivity and trade volume are averaged for each bin, and then over time. Panel A shows the average VIX sensitivity for each bin and Panel B shows the average volume at VIX settlement. Panel C compares the settlement volume with average volume over the rest of the day, day before, and day after.

Panel C: Put Options Volume at Settlement versus Daily Volume on Other Days



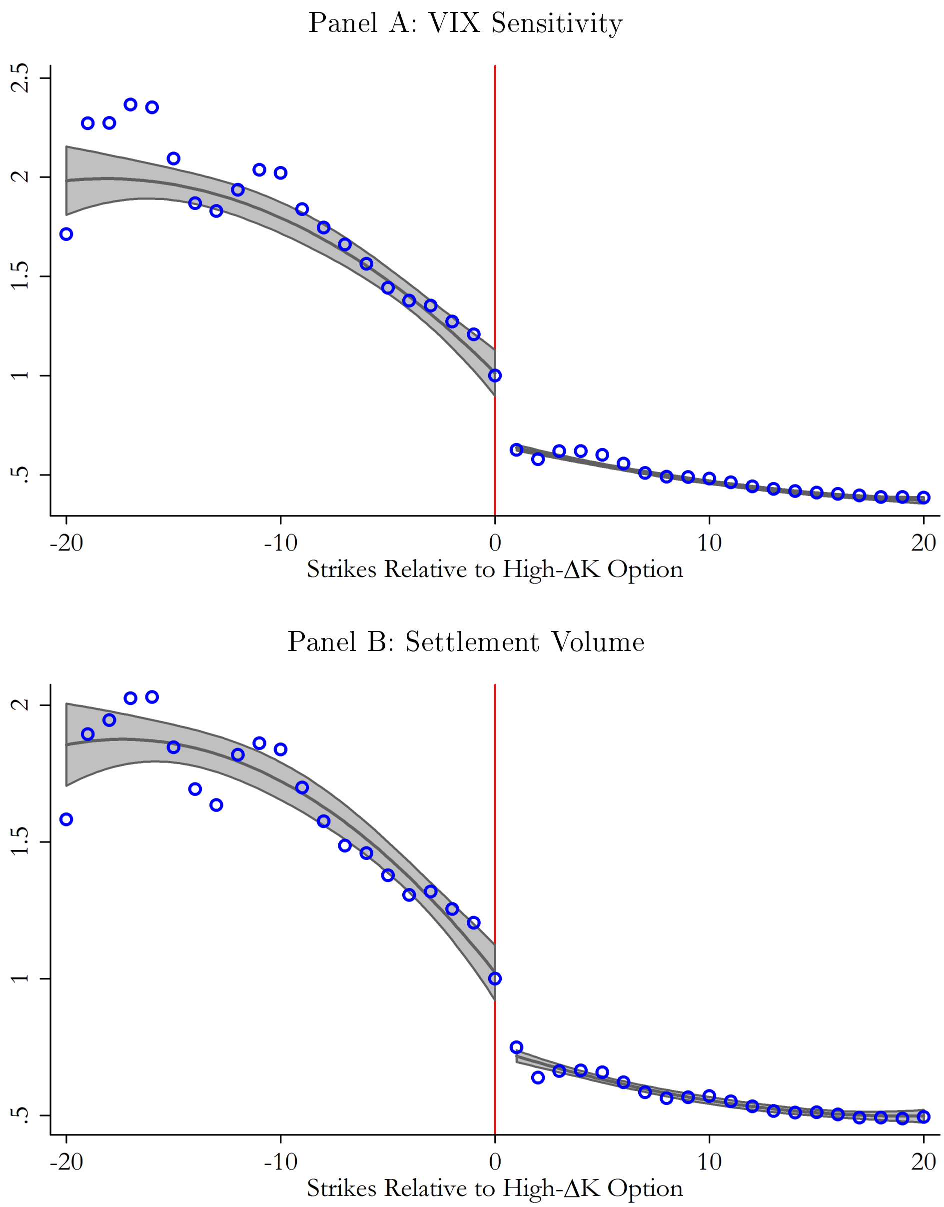


Figure 3. Discontinuity in VIX Sensitivity and Trade Volume of Put Options. This figure shows the discontinuity in VIX sensitivity and trade volume of put options due to the jump in strike prices. The sample consists of the options used in VIX settlement calculations from January 2008 to April 2015. A jump is defined as when ΔK (the average distance between a strike price and strike prices above and below) increases for an option relative to the adjacent strike. The center vertical lines represent the strike with high ΔK at the jump. The strike prices above and below the jumps are ranked relative to the strikes at the jump. Then VIX sensitivity and settlement volume are normalized by the values of these variables for the High-ΔK strike at the jump. The blue circles show the average of these variables for each rank across different settlements. Panel A shows the jump in VIX sensitivity and Panel B shows the jump in trade volume at settlement. The gray areas represent the 95% confidence interval for the fitted values of the variable on the y-axis as a quadratic function of the rank of options relative to the High-ΔK option.

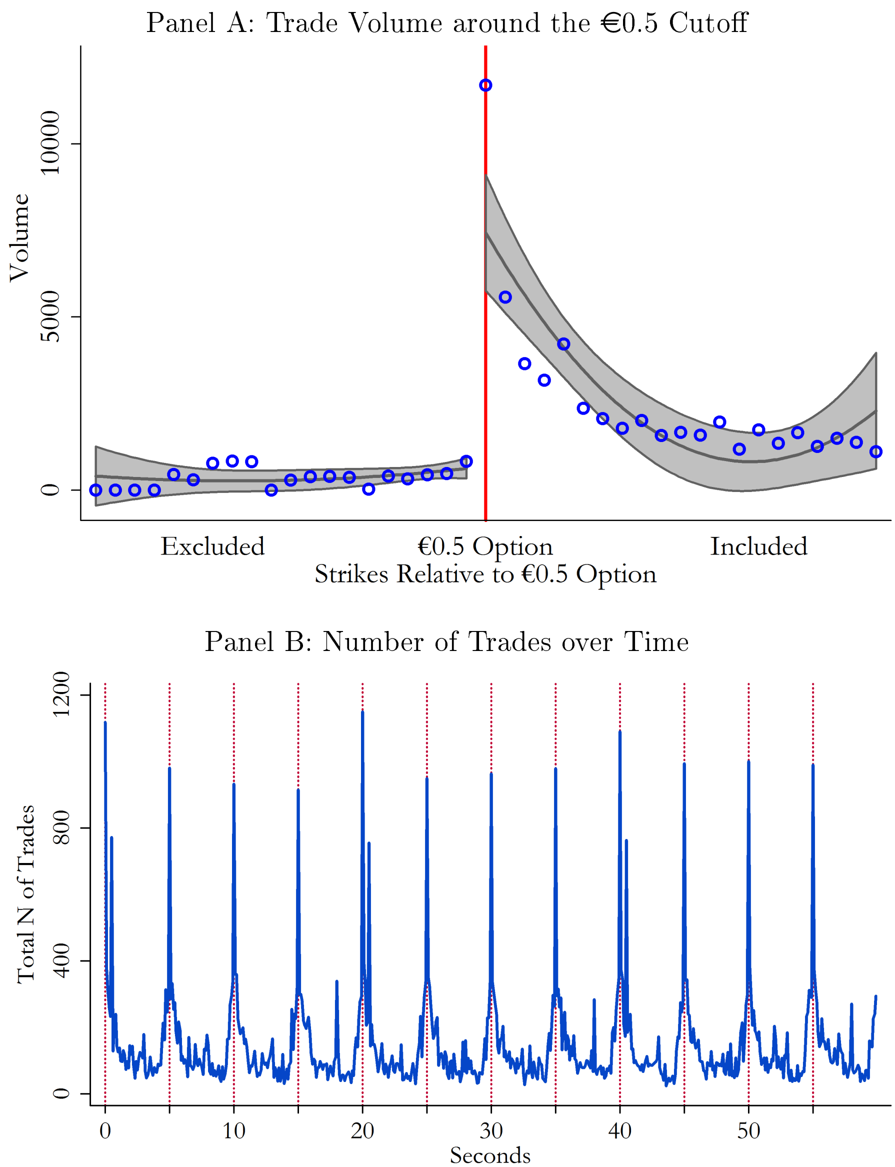


Figure 4. Trading Pattern of EURO STOXX 50 Put Options during the VSTOXX Settlement. Panel A shows the volume across strikes of EURO STOXX 50 put options around the €0.5 cutoff. For each strike, the average price over the settlement window, weighted by settlement volume, is calculated and rounded to the nearest tick. Then the strikes are sorted relative to the deepest OTM strike with the average price of €0.5. The blue circles show the average volume for strikes sorted relative to the €0.5 option across settlements. The gray areas represent the 95% confidence interval for the fitted values of the volume as a quadratic function of the ranks relative to the cutoff. Panel B shows the time clustering of trades during the settlement. Each five-second interval is divided into 50 buckets of 100 milliseconds each. The first five minutes of each settlement is used to identify the bucket with the highest number of trades, and the clock is set to zero at the time of that bucket. The graph reports the total number of trades for the 100-millisecond buckets across each minute of the next 25 minutes of the settlement period over the sample period. The sample consists of the settlement days from January 2014 to August 2015.

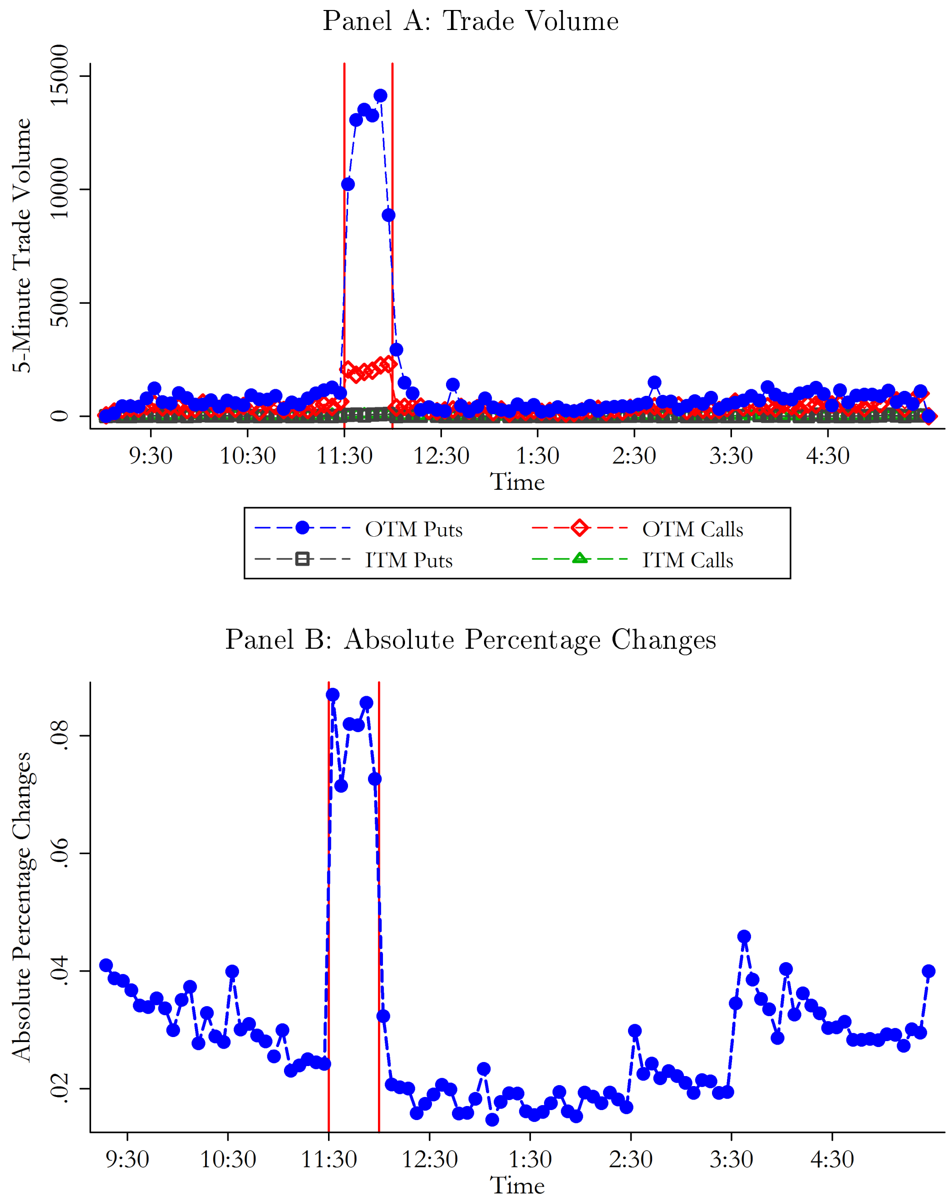
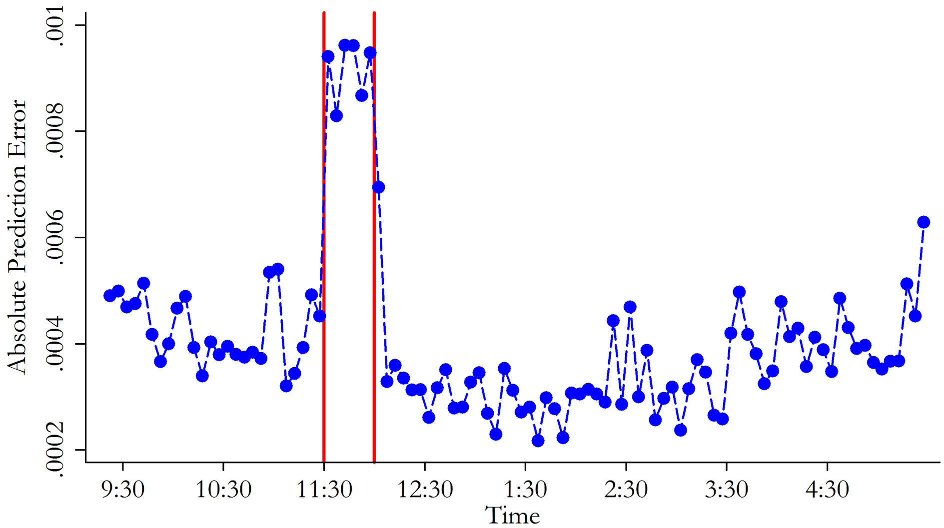
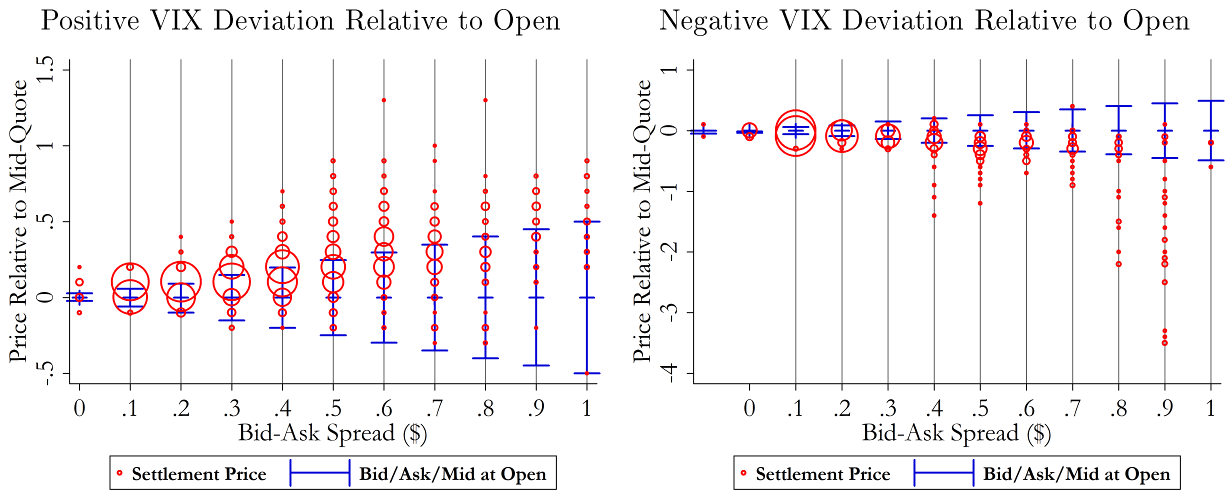


Figure 5. Trade Volume, Absolute Changes, and Prediction Error in VSTOXX Index on Settlement Days. Panel A shows the trade volume of EURO STOXX 50 options during the settlement days, aggregated every five minutes and averaged across the settlements. Panel B shows the absolute percentage changes of VSTOXX index on settlement days, calculated as the absolute value of five-second percentage changes in the index value, averaged every five minutes. The sample consists of the settlement days from January 2014 to August 2015. Panel C shows the out-of-sample prediction errors from five-minute rolling OLS regression of VSTOXX on EURO STOXX 50 index. The sample consists of the settlement days from March 2015 to August 2015. The red vertical lines mark the 30-minute window when the VSTOXX settlement value is calculated. The data is reported every five seconds for the VSTOXX index and every 15 seconds for the STOXX index.

Panel C: Absolute Prediction Errors



Panel A: SPX Option Prices at Settlement Relative to the Quotes at Open



Panel B: SPX Option Prices at Settlement Relative to the Quotes at Previous Close

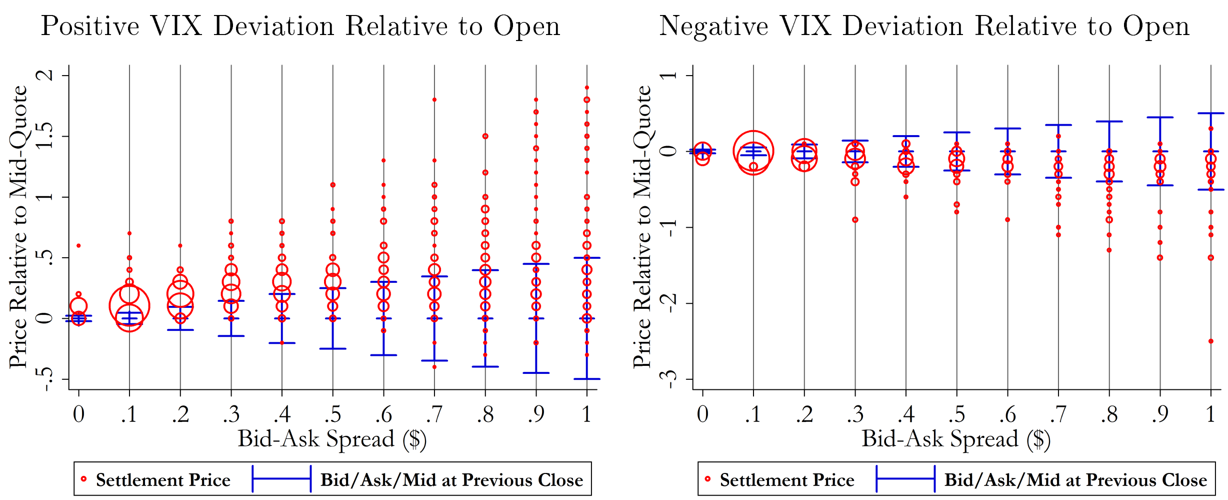


Figure 6. SPX Put Options Settlement Prices Relative to the Spread at Benchmark. These figures show the prices of individual SPX put options at settlement relative to the bid, ask, and mid-quote of the options at the market open immediately after the settlement (Panel A) and at the close the day before (Panel B). Positive deviation days are those with 20bp or greater deviation in VIX at settlement and negative deviation days are those with -20bp or less deviation. The sample consists of the settlement days from May 2010 to April 2015. Options are pooled into the bins based on their round bid-ask spread at 10-cent intervals and then across different settlement days. The graph shows options with a spread of $1 or less. For options with missing quotes or quotes that are strictly inferior to other strikes in the same option series, we use quotes of options that strictly dominate that option, i.e. the best ask of the more ITM options or the best bid of the more OTM options. The red bubbles show the settlement prices, and their size is proportional to the number of individual SPX options in each group.

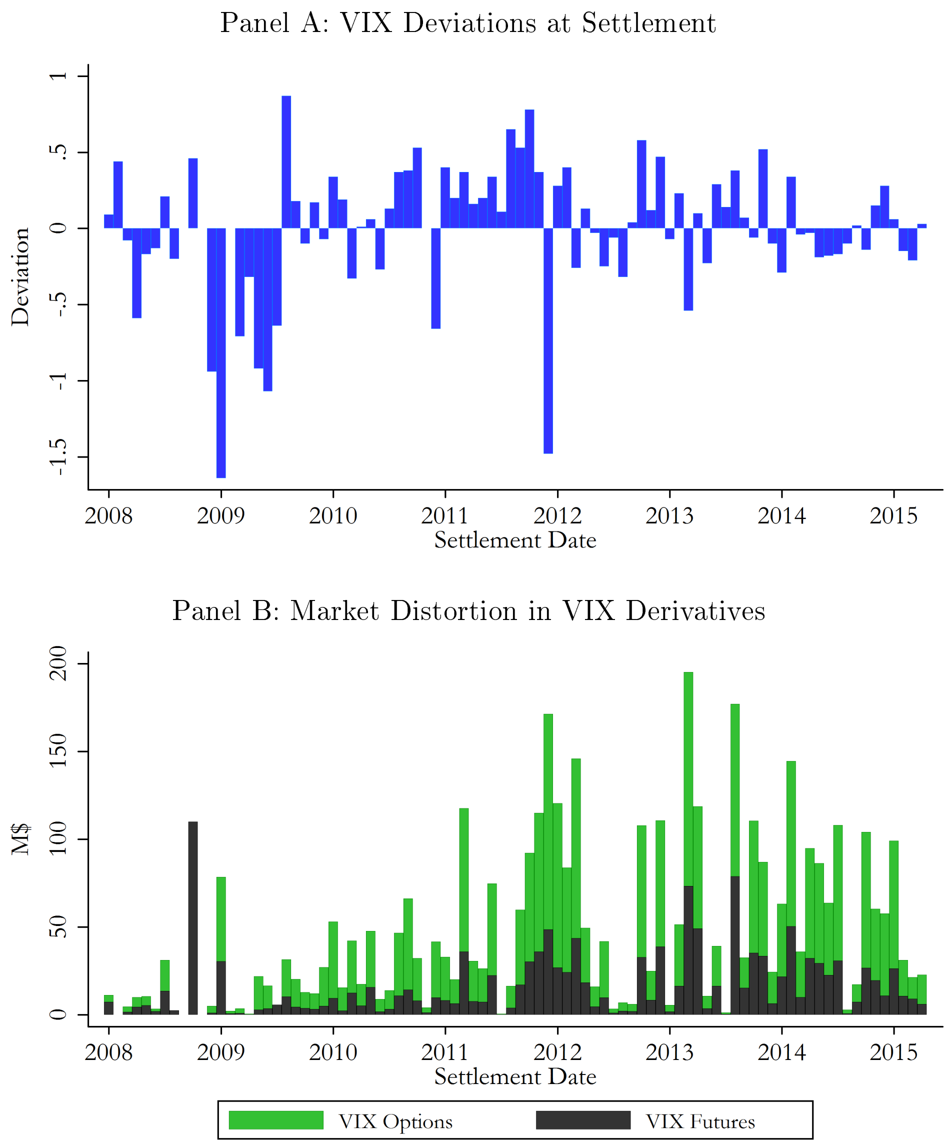
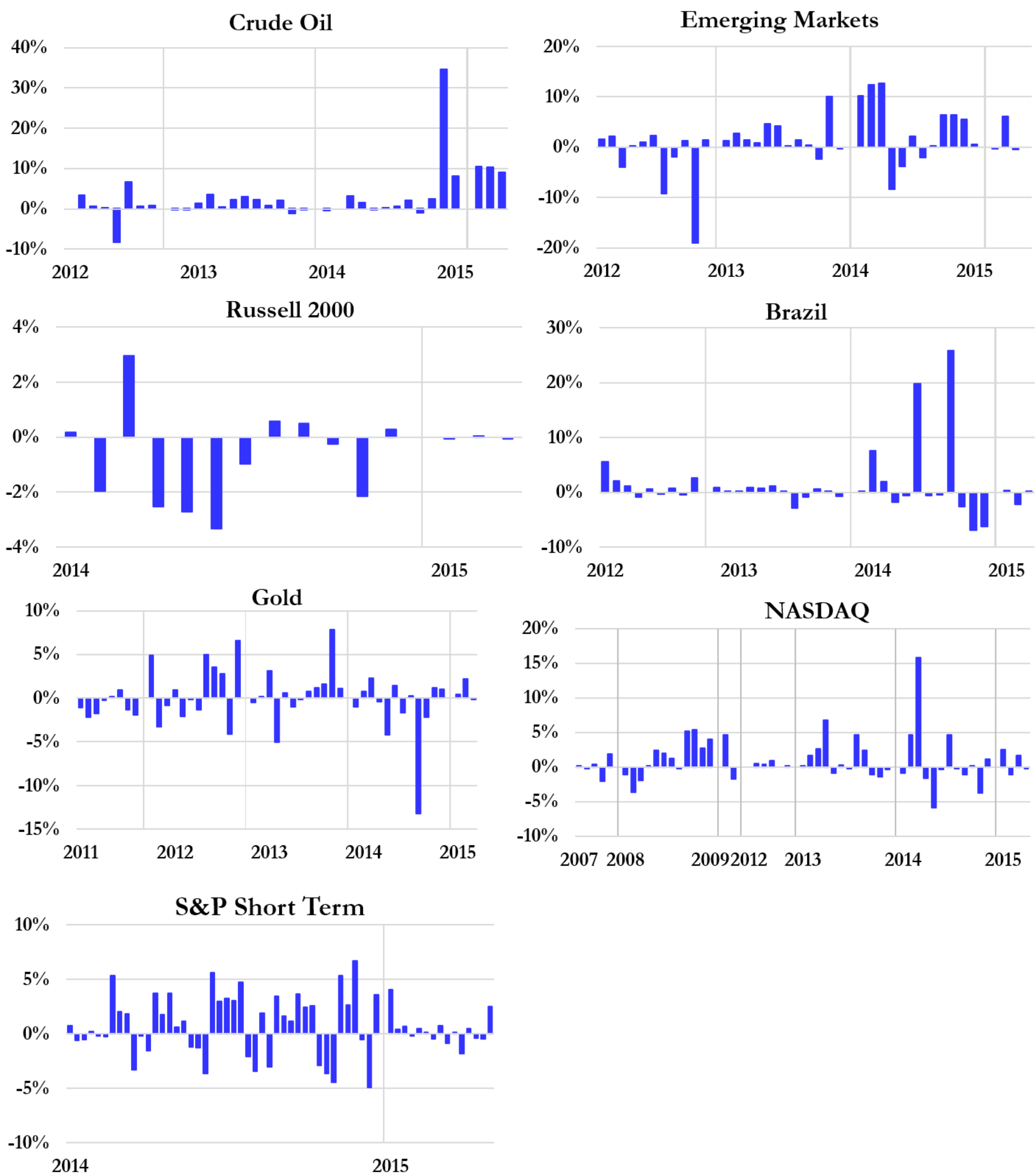
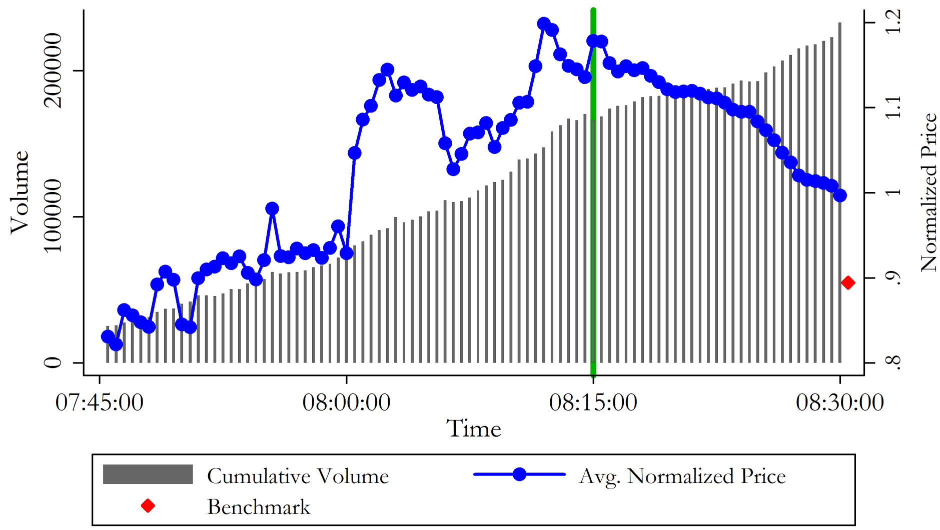


Figure 7. Deviation of Volatility Index Settlement and Market Distortion in VIX Derivatives. Panel A shows the deviations in VIX settlements relative to the benchmark VIX calculated using the mid-quotes of SPX options shortly after the settlement, where settlement and open benchmark are calculated using the same range of options included in both settlement and the open. If the required series of individual SPX options does not open within 70 seconds after the market opens, the difference between the VIX settlement and the disseminated daily open price of VIX is used. The sample consists of the settlement dates from January 2008 to April 2015. Panel B shows the market distortions in VIX options and futures caused by VIX settlement deviations, calculated as the open interest of VIX futures and ITM VIX options on close of the day before settlement multiplied by the settlement deviation. Panel C plots the settlement deviations for other volatility indices, as benchmarked by open value of the index and as a percentage of the open index. Data is available from 2012 to 2015 for crude oil, emerging markets, and Brazil ETFs; from 2011 to 2015 for gold; from 2014 to 2015 for Russell 2000 and S&P Short Term; and from 2007 to 2009 and 2012 to 2015 for NASDAQ.

Panel C: Deviations in Other Volatility Indices



Panel A: Months with Positive Deviation (Average)



Panel B: Months with Positive Deviation (25, 50, and 75 Percentiles)

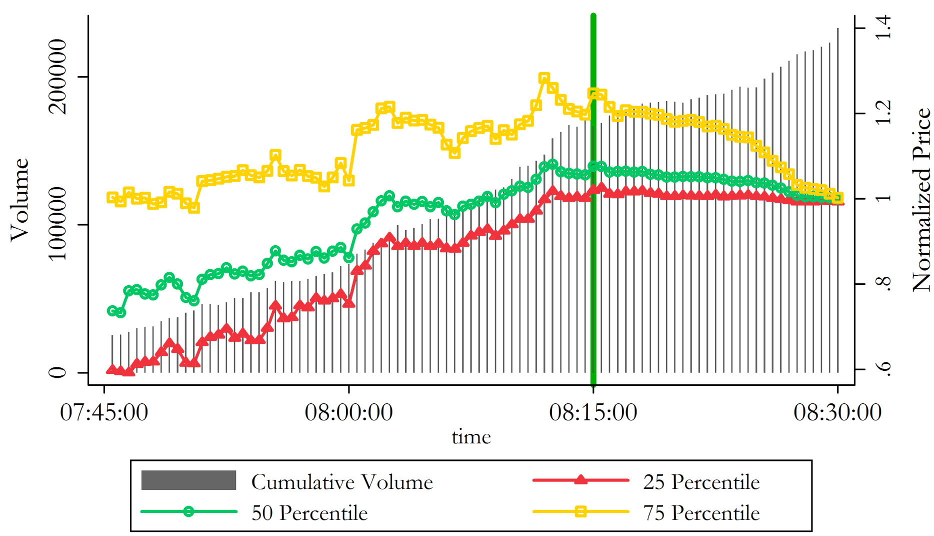


Figure 8. Price Movements of Put SPX Options before Market Open. This figure shows the change in indicative price of put SPX options over time on settlement days with positive deviations, as reported in CBOE Imbalance Reports. Prices of all put options used in settlement are normalized by their settlement price and then averaged across all strike prices and over settlement dates. Panel A shows the averages and Panel B the 25, 50, and 75 percentiles for days with positive VIX settlement deviation of more than 20bp. (March 2013 and October 2014 are removed from the sample because SPX option series do not have quotes in the data immediately after market open.)

Table 1. Trade Volume of OTM Options on Settlement Days. This table shows OLS estimates where the dependent variable is daily trade volume of the SPX options in a regression of the form:

$$Volume_{it} = \beta_0 + \beta_1 SettlementDay_t + \beta_2 OTM_{it} + \beta_3 SettlementDay_t * OTM_{it} + \alpha_t + \epsilon_{it}$$

where $SettlementDay_t$ is a dummy variable that takes the value of one if the day is a VIX settlement day, and zero otherwise, OTM_{it} is a dummy variable equal to one if option i at settlement time t is out-of-the-money and equal to zero if in-the-money, and α_t is the expiration date fixed effect. The last two columns exclude trades that occurred during the preopening settlement on settlement days but include trades in the rest of the settlement day. The sample consists of the option chains used in the settlement dates from January 2008 to April 2015. Reported t-statistics in parentheses are clustered by the options' expiration date.

	Including Settlement Trades		Excluding Settlement Trades	
	Volume	Volume	Volume	Volume
Settlement Day	57.02	54.07	-33.73	-34.24
	(1.06)	(0.99)	(-0.72)	(-0.71)
OTM	1011.3***	1067.3***	1009.7***	1066.1***
	(15.47)	(16.55)	(15.45)	(16.40)
Settlement Day × OTM	1176.2***	1177.9***	118.2*	116.9
	(11.86)	(11.63)	(2.00)	(1.94)
Constant	509.0***	1580.9***	508.6***	1348.1***
	(10.24)	(28.61)	(10.24)	(26.00)
ExDate FE	No	Yes	No	Yes
Observations	55,542	55,542	55,542	55,542
Adjusted R^2	0.027	0.043	0.009	0.022

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2. Effect of VIX Sensitivity on Trade Volume. This table shows the relationship between trade volume of monthly SPX options and the sensitivity of VIX to price changes in these options in a regression of the form:

$$Volume_{it} = \beta_0 + \beta_1 VIXSensitivity_{it} + \alpha_t + \epsilon_{it}$$

where $VIXSensitivity_{it}$ is constructed by calculating the absolute change in VIX settlement value as a result of five-cent price changes in strike i at time t, holding all the other prices constant, and α_t is the date fixed effect. The sample consists of the option chains used in the settlement dates from January 2008 to April 2015. Reported t-statistics in parentheses are clustered by date.

	At Settlement		At Other Times		
	Settle Vol.	Settle Vol.	Day Before	Rest of the Day	Day After
VIX Sensitivity	5407.3***	5577.5***	-1427.9***	-1147.1**	-1507.2**
	(3.50)	(3.60)	(-4.08)	(-2.80)	(-3.40)
Constant	690.6***	1014.4***	2057.8***	3759.4***	5142.6***
	(3.80)	(6.09)	(54.74)	(85.46)	(108.03)
Date FE	No	Yes	Yes	Yes	Yes
Observations	11,788	11,788	11,787	11,787	11,787
Adjusted R^2	0.324	0.511	0.028	0.029	0.022

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3. Effect of Non-Settlement Liquidity and VIX Sensitivity on Volume. This table shows the relationship between settlement volume of monthly SPX options and their liquidity in non-settlement times as well as their VIX sensitivity in regressions of the form:

$$Volume_{it} = \beta_0 + \beta_1 Liquidity_{it} + \beta_2 \Delta K_{it} + \alpha_t + \epsilon_{it}$$

and

$$Volume_{it} = \beta_0 + \beta_1 Liquidity_{it} + \beta_2 VIXSensitivity_{it} + \alpha_t + \epsilon_{it}$$

where $VIXSensitivity_{it}$ is constructed by calculating the absolute change in VIX settlement value as a result of five-cent price changes in strike i at time t, holding all the other prices constant, and $Liquidity_{it}$ is measured as either the average of prior 30 days' volume or the average of prior 30 days' inverse percentage bid-ask spread. ΔK_{it} is the average distance between the strike i and strikes above and below, and α_t is the date fixed effect. The sample consists of the option chains used in the settlement dates from January 2008 to April 2015. Reported t-statistics in parentheses are clustered by date.

	Call Options Volume		Put Options Volume			
	(1)	(2)	(3)	(4)	(5)	(6)
Liquidity (Volume)	0.0377***		-0.0466***		-0.0293*	
	(6.33)		(-6.70)		(-2.16)	
Liquidity (Inv. Pct. Spread)		821.9**		-3370.2***		-2208.2
		(3.21)		(-4.48)		(-1.79)
Delta K	88.05***	88.96***	441.9***	434.2***		
	(7.27)	(7.40)	(5.51)	(5.34)		
VIX Sensitivity					5364.7**	5275.1**
					(3.33)	(3.19)
Constant	362.2***	211.4*	-1263.1*	-1019.8	1448.3***	1581.3***
	(5.08)	(2.33)	(-2.01)	(-1.55)	(6.25)	(5.25)
Date FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,129	3,129	7,097	7,097	7,097	7,097
Adjusted R^2	0.699	0.694	0.575	0.578	0.508	0.510

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4. Absolute Changes and Prediction Error in VSTOXX Index on Settlement Days. Column (1) presents the OLS regression of absolute five-second percentage changes of the VSTOXX index on dummy variables for each five-minute interval during the settlement days. The sample consists of the settlement days from January 2014 to August 2015. Column (2) shows the OLS regression of prediction errors of the VSTOXX index using EURO STOXX 50 as the predictor on dummy variables for each five minute interval. Prediction errors are calculated using five-minute rolling OLS regressions of VSTOXX on EURO STOXX 50 index. The sample consists of the settlement days from March 2015 to August 2015. Reported t-statistics in parentheses are clustered by settlement date in column (1).

	(1) Abs. Pct. Changes	(2) Abs. Prediction Error
11:05:00-11:09:59	-0.0135**	-0.000148*
	(-3.43)	(-2.44)
11:10:00-11:14:59	-0.0129**	-0.000125*
	(-3.57)	(-2.05)
11:15:00-11:19:59	-0.0115**	-0.0000762
	(-3.12)	(-1.17)
11:20:00-11:24:59	-0.0116**	0.0000233
	(-3.72)	(0.30)
11:25:00-11:29:59	-0.0128***	-0.0000168
	(-5.50)	(-0.26)
11:30:00-11:34:59	0.0491***	0.000472***
	(4.78)	(4.58)
11:35:00-11:39:59	0.0354***	0.000360**
	(4.12)	(3.25)
11:40:00-11:44:59	0.0455**	0.000492***
	(3.87)	(4.57)
11:45:00-11:49:59	0.0569**	0.000492***
	(3.19)	(4.31)
11:50:00-11:54:59	0.0491*	0.000399***
	(2.64)	(4.08)
11:55:00-11:59:59	0.0362**	0.000479***
	(3.02)	(4.50)
12:00:00-12:04:59	-0.00411	0.000226*
	(-1.03)	(2.37)
12:05:00-12:09:59	-0.0157***	-0.000140*
	(-4.58)	(-2.25)
12:10:00-12:14:59	-0.00590	-0.000110
	(-0.52)	(-1.76)
12:15:00-12:19:59	-0.0162***	-0.000134*
	(-4.12)	(-2.23)
12:20:00-12:24:59	-0.0206***	-0.000156*
	(-6.27)	(-2.33)

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5. Liquidity and Market Size of SPX Options and VIX Derivatives. This table compares the liquidity and market size of the lower-level SPX options and upper-level VIX derivatives. Panel A shows the summary statistics for spread between the VIX values calculated from SPX options bid and ask prices (VIXB and VIXA respectively) at the market open of settlement days from January 2008 to July 2015. The spread is winsorized at the 2.5% level at each end. Panel B shows the summary statistics for the bid-ask spread of the VIX futures with less than ninety days to maturity from January 2008 to July 2015. Panel C shows the average ratio of the amount of Vega of VIX derivatives exposed to the settlement relative to the total Vega traded in the SPX options at settlement, from January 2008 to April 2015. The Vega of the VIX derivatives is calculated as the sum of the Vega of open VIX futures and in-the-money VIX options. The Vega of SPX options is the sum of the Vega of all the SPX options traded at settlement, computed using the Black-Scholes model.

Panel A: Spread between VIX-Ask and VIX-Bid at Open after Settlements

Variable	Mean	Std. Dev.	P10	P50	P90
Spread	1.55	1.289	0.46	1.08	3.73
Percentage Spread	6.80	3.54	3.07	6.05	12.47

Panel B: VIX Futures Bid-Ask Spread

Variable	Mean	Std. Dev.	P10	P50	P90
Futures Spread	0.071	0.055	0.05	0.05	0.1
Futures Percentage Spread	0.32	0.16	0.17	0.29	0.51

Panel C: Ratio of VIX Derivatives Vega Notional to Traded SPX Options at Settlement

Variable	VIX Futures	VIX Options	VIX Futures and Options
Equally Weighted	5.7	7.3	13.0
Value Weighted	4.7	6.3	11.0

Table 6. SPX Options Price Movements on Settlement Days. This table shows the changes in the price of SPX options on settlement days from before the market opens to right afterward. For each SPX option included in the settlement, four different prices are calculated: price before 8 am (average price between 7:45 and 8 am), price around 8:15 am (average price between 8:14 and 8:16 am), price around 8:30 am (average price between 8:29 and 8:30 am), and the benchmark price right after the market opens. The table reports the differences between the average option prices for each two consecutive time periods ($price_t - price_{t-1}$). Positive deviation days are those with 20bp or greater deviation in VIX settlement and negative deviation days are those with -20bp or less deviation. The sample consists of the settlement days from May 2010 to April 2015. (March 2013 and October 2014 are removed from the sample because SPX option series do not have quotes in the data immediately after market open.) Reported t-statistics in parentheses are for paired t-test of difference in mean and are clustered by settlement date.

	Positive Deviation	Negative Deviation
Changes before 8 to 8:15 am	0.726***	-0.0984
	(3.88)	(-1.04)
Changes from 8:15 to 8:30 am	-0.217***	0.0923*
	(-3.58)	(2.25)
Changes from 8:30 am to Market Open	-0.175***	0.180**
	(-14.40)	(2.70)
Changes from Market Open to 8:45 am	-0.0163	-0.0213
	(-0.29)	(-0.59)
Observations	2,970	1,227

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$