The Stock Market Impact of Volatility Hedging: Evidence from End-of-Day Trading by VIX ETPs

Christine Bangsgaard*[a] and Thomas Kokholm†[a,b]

[a]Aarhus BSS, Aarhus University, Department of Economics and Business Economics, Denmark

[b]Danish Finance Institute

Working paper

Abstract

VIX futures market makers can hedge their volatility exposure by trading SPX options and SPX futures. To proxy for the hedging activities in SPX futures by VIX futures market makers, we compute the end-of-the-day VIX futures demand by VIX ETPs over an extended period, and find that the demand impacts the SPX futures market in the direction consistent with the VIX futures hedging channel. The VIX ETP demand is a strong predictor of the end-of-day SPX futures return both in-sample and out-of-sample, and historically it has been possible to monetize the hedging impact. The subsequent reversal provide evidence that the VIX futures hedging channel can move the SPX futures market for reasons unrelated to price discovery.

Keywords: Price impact; volatility hedging; VIX futures; VIX ETPs

JEL codes: G13, G14, G23

*chba@econ.au.dk

†thko@econ.au.dk

1 Introduction

The market for VIX futures has witnessed impressive growth since the introduction of the first VIX futures contract in 2004 on the Chicago Board of Options Exchange (CBOE) and the VIX index itself has become a widely recognized yardstick of stock market risk. Since their launch, VIX futures gained popularity as tools to hedge volatility exposure or diversify portfolios (Whaley, 2009). In 2009, the first VIX Exchange-Traded Product (ETP) hit the market and, since then, investors have increasingly used products tied to VIX futures to speculate in future volatility outlook (Bollen et al., 2017; Bhansali and Harris, 2018). Typically, major dealers in financial markets take the other side of the VIX futures trade. Market makers and dealers are subject to strict risk requirements and profit from their flow of transactions and not from risk-taking. In order to hedge their positions in volatility, dealers typically employ various options-based hedging strategies (Chang, 2017). As part of the hedging strategy, it is necessary to trade the underlying index which, in practice, is done by trading SPX futures. This creates a channel for spillover effects to the broad stock market.

In this paper, we analyze the nature of the hedging channel by studying how the VIX ETP issuers' demand for VIX futures impacts the SPX futures market. Since their VIX futures demand is concentrated at the end of the trading day, this generates an end-of-day hedging demand in SPX futures by the VIX futures market makers. As a proxy for the end-of-day SPX futures trading by the market makers, we therefore use the VIX futures demand of VIX ETPs. In line with this explanation, we find that the VIX futures trades by VIX ETPs move the SPX futures market in the direction implied by the hedging channel. Overall, our results reveal that the VIX futures demand of VIX ETPs is a strong predictor of end-of-day SPX futures returns. Using only the information contained in the proxy, we are able to explain 4.5% of the in-sample variation in end-of-day returns. The out-of-sample validity of our predictor is illustrated by an out-of-sample R-squared of 4.0% for the most simple model. We also show the economic significance of the price impact by forming trading strategies based on the measure of hedging activities as a signal. The trading strategies are profitable and outperform benchmark strategies in terms of risk-adjusted returns. Since the trading in VIX futures by VIX ETPs is driven by hedging needs, we expect that these trades are generally uninformed (a view which has received empirical support by e.g. Fernandez-Perez et al. (2019); Brøgger (2021); Todorov (2021)). By documenting a reversal in the SPX futures prices following the hedging trades of VIX ETPs, we confirm this belief and provide evidence consistent with a transitory SPX futures price impact from VIX futures hedging activities.

The findings have relevance for policymakers who are concerned about market fragility. If hedging activities of VIX futures dealers have the potential to destabilize or magnify market drops, it is vital for regulators to understand the driving mechanisms behind the price movements.[1] In fact, regulators are starting to worry that, due to the rebalancing of the hedge ratios of dealers, a sudden increase in volatility or a drop in the underlying can trigger a sell-off of the underlying that magnifies the market decline (Bank for International Settlements, 2018). The market movements on February 5 2018 (later labeled as the volmaggedon) serve as anecdotal evidence in support of this belief. On this day the VIX spiked and incurred the largest relative move of 116% since its inception in 1993. The sharp increase in the VIX was accompanied by a drop to the SPX index of 4.1%. These movements materialized despite the fact that no clear macro-economic event occurred (Augustin et al., 2021).

The presence of hedging activities by VIX futures dealers can influence the SPX futures market in two ways: If VIX futures trading is informative, the hedging activities of VIX futures market makers help transmit information from the VIX futures to the SPX futures markets. On the other hand, if VIX futures trading is uninformative, hedging activities could push SPX futures prices away from their true value. While Bangsgaard and Kokholm (2022) find some indication that VIX futures hedging influences the lead-lag relation between VIX futures and SPX futures, it remains unclear whether the hedging channel increases or decreases the efficiency of the SPX futures market. By relying on the uninformed and liquidity-driven VIX futures trading by VIX ETPs, we study whether VIX futures hedging activities generate temporary price changes in the SPX futures market. Figure 1 illustrates the connection between

[1]Furthermore, price changes in the futures market may spread to the underlying index as arbitrage activities maintain a tight link between the two markets (Baltussen et al., 2019; Ben-David et al., 2018).

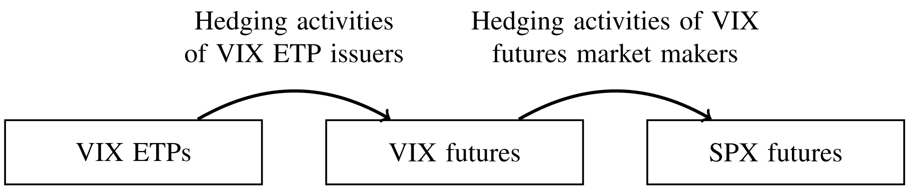

Figure 1: The connection between VIX ETP issuers, VIX futures market makers and the SPX futures market.

VIX ETPs, VIX futures and SPX futures that we exploit to test if the SPX futures market is impacted by the VIX futures hedging activities.

For hedging of other derivatives, empirical evidence has supported the presence of both informational and non-informational channels. In relation to option market makers, Hu (2014) show that the trades in the underlying security associated with setting up delta hedges are related to permanent price changes to the underlying stocks. Option dealers' delta hedging has also been found to temporarily impact the underlying of the option as dealers rebalance their hedge. In particular, measures related to the sign and size of the aggregate gamma exposure of a given asset is found to be a significant predictor of returns at the end of the trading day in Baltussen et al. (2021); Barbon et al. (2022). In a related study, Barbon and Buraschi (2021) study the impact of the gamma exposure on intraday returns. The research is also related to the literature on stock-pinning, namely the phenomenon that option dealers' hedging demands can change the dynamics of the price of the underlying security. This is shown by Avellaneda and Lipkin (2003); Ni et al. (2005); Golez and Jackwerth (2012), who find that if the open interest of an option for a given strike is sufficiently large, delta hedging of dealers can push the stock price to the strike price of the option at the option expiration.

The remainder of the paper is structured as follows: First, Section 2 details the channels through which VIX futures hedging can impact SPX futures. Next, Section 3 describes the data followed by an introduction to VIX ETPs, the rebalancing demand of the VIX ETP issuers, and an explanation of the overall empirical strategy. In Section 4, we present the results, and Section 5 concludes.

2 Hedging induced market spillovers

Market makers in VIX futures typically risk-manage their volatility exposure by trading other volatility-sensitive products such as European options. For instance, a new position in a VIX futures (VX) can be hedged with a delta-hedged position in a European option on the SPX index. Hence, trading in VIX futures leads to subsequent trading in the underlying index, which in the context of VIX futures, is typically carried out via SPX futures (ES). Consider a dealer with a short position in a VIX futures contract with price P_t^{VX}. The dealer hedges by buying options on the SPX index while delta hedging using SPX futures. Denote by P_t^{ES} the price of the SPX futures used for hedging and by V_t its instantaneous volatility. In order to obtain zero sensitivity to changes in the SPX futures (i.e. a delta neutral hedge) to the short VIX futures position, the dealer invests in X_t^Q option contracts (either calls or puts) with price P_t^Q and in X_t^{ES} contracts of the underlying SPX futures simultaneously. Hence, at any given point in time t the dealer faces the two equations:

$$-\frac{\partial P_t^{VX}}{\partial V_t} + \frac{\partial P_t^Q}{\partial V_t} X_t^Q = 0 \tag{1}$$

$$X_t^{ES} + \frac{\partial P_t^Q}{\partial P_t^{ES}} X_t^Q = 0. \tag{2}$$

Solving equation (1) reveals that to obtain zero sensitivity to changes in volatility, the amount of options the dealer has to enter equals

$$X_t^Q = \frac{\partial P_t^{VX}/\partial V_t}{\partial P_t^Q/\partial V_t}. \tag{3}$$

Since this is a positive quantity, the dealer should buy SPX options. Solving (2) reveals that

$$X_t^{ES} = -\frac{\partial P_t^Q}{\partial P_t^{ES}} X_t^Q \tag{4}$$

such that $X_t^{ES} < 0$ if call options are used to hedge the volatility exposure, and $X_t^{ES} > 0$ if put options are used. In principle, the dealer can enter into put or call options. However, in practice, the dealer has to buy call options since this matches the short position of the end-user demand who tend to be long in SPX put options and short in SPX call options (Garleanu et al., 2009; Goyenko and Zhang, 2019). As shown above, the positive delta of the call position has to be hedged by a short SPX futures position.

Alternatively, dealers could turn to a more approximate hedge utilizing the negative correlation between VIX futures and SPX futures prices. Under this approach, long demand in VIX futures (short position of the dealer) is simply hedged by a short position in SPX futures. In either case, the result is SPX futures selling pressure.

In the opposite case where the VIX futures market maker hedges a long VIX futures position, the position in equation (3) has the opposite sign, and the dealer has to enter a short option position. In order to match the end-user demand, the dealer should now use put options to match the volatility exposure of the long VIX futures position. For a put option, the expression for the SPX futures position in equation (4) implies that the SPX futures position should again be short. On the other hand, the approximate hedging strategy relying on the negative correlation of the VIX futures and SPX futures, would prescribe that dealers take a long SPX futures position. Given that dealers could use either of the two approaches, there is less certainty about how dealers will trade SPX futures when hedging a long VIX futures position. This is different from the case of hedging a short VIX futures position where both hedging strategies require that dealers sell SPX futures. Hence, the impact of the hedging activities is possibly asymmetric depending on the sign of the VIX futures demand. Specifically, the above suggests that the VIX futures hedging channel would be more likely to affect the SPX futures market when dealers are hedging a short VIX futures position.

Through the hedging of a short VIX futures exposure (long demand), market makers run the risk of being part of the feedback cycle illustrated in Figure 2. First, the long VIX futures demand triggers SPX futures selling by VIX futures dealers. In turn, this moves the SPX futures market price and therefore forces SPX option dealers to rebalance. When option dealers are negative gamma, the initial impact on the SPX futures price from VIX futures hedging may generate further SPX futures selling as option market makers rebalance their hedges. In

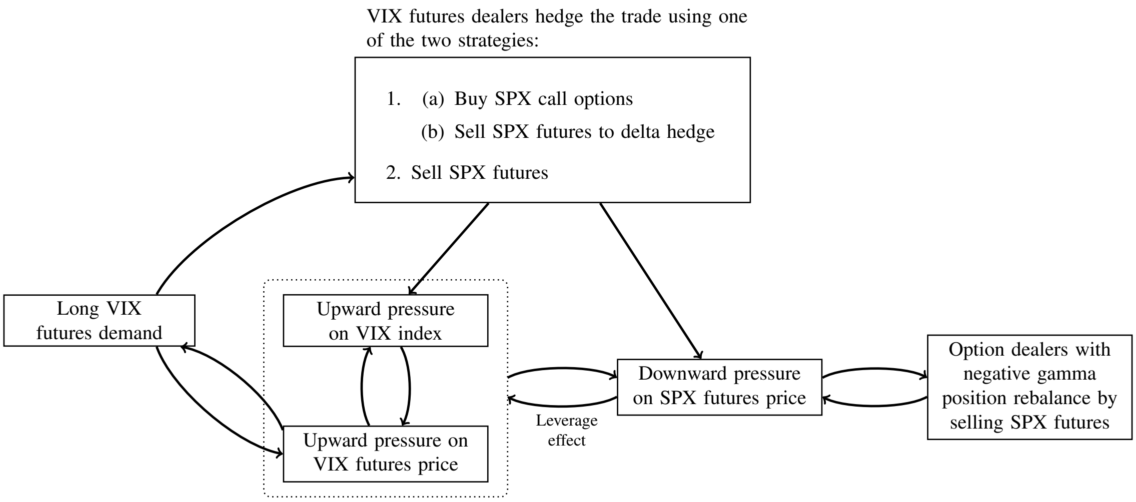

Figure 2: Feedback effect from initial long demand in VIX futures.

addition, large demand in long VIX futures is typically associated with a distressed stock market where end-user demand in long put options is high and the aggregate gamma position of dealers negative. For this reason, the negative gamma position of options dealers is a potential amplifier of the VIX futures hedging mechanism's impact on the SPX futures market.

The situation depicted in Figure 2 also involves an increase in volatility. The reason that VIX futures buying leads to increasing volatility and VIX futures prices are twofold: Firstly, the SPX futures selling pressure from the hedging strategy may increase volatility via the leverage effect. Secondly, since the hedging strategy does not only involve trading SPX futures but also SPX options, the spillovers from VIX futures hedging activities may not be limited to the SPX futures market. In fact, buying SPX options will work to increase the level of the VIX index.[2] Due to the close connection between the VIX index and the VIX futures market, this spills over to the VIX futures in the form of increasing prices. The full feedback cycle materializes as increasing volatility and VIX futures prices can generate additional VIX futures demand, which creates more VIX futures hedging activity and thereby SPX futures selling pressure. For instance, for both leveraged and inverse VIX ETP issus, demand in long VIX futures increases

[2] Empirical evidence suggests that VIX futures lead the VIX index (Shu and Zhang, 2012; Frijns et al., 2016; Bollen et al., 2017; Chen and Tsai, 2017). The common interpretation of this is that this is a result of the greater information content in VIX futures as opposed to the VIX index. Although not being the scope of this paper, the VIX futures lead can also be the consequence of dealers hedging their VIX futures exposure in the SPX options markets.

when the underlying VIX futures price increases (see e.g. Brøgger (2021)).

3 Data and empirical strategy

In this section, we explain the overall approach to empirically test if VIX futures hedging activities generate price impact on the SPX futures. First, Section 3.1 introduces the data used for the analysis, while Section 3.2 introduces the VIX ETPs and describes how they trade VIX futures. Section 3.3 details how the VIX ETP demand can be used to analyze if VIX futures hedging impacts the SPX futures market. The methodology used to estimate the VIX ETP rebalanding demand for VIX futures is presented in Section 3.4. Finally, descriptive statistics of the computed time series of VIX ETP demand as well as for the chosen control variables are reported in Section 3.5.

3.1 Data

For the analysis, we use a sample period from January 2013 to September 2020. We use data on E-mini S&P 500 futures and VIX futures. Both futures contracts trade only on a single exchange: VIX futures on CFE and SPX futures on CME Globex. They both trade nearly 24 hours a day five days a week. The SPX futures and VIX futures regular trading hours is 9:30-16:15 EST.[3] For the SPX futures there is a trading halt from 16:15 to 16:30. This is followed by a 30 minutes window of trading until 17:00 whereafter trading is again halted until a new session begins at 18:00. For each sample date, we use the SPX futures contract which is closest to expiry except when the time to expiry is less than six days where we shift to the next contract. For the VIX futures, we use both the front-month and second-month contracts which are the contracts relevant for the short-term VIX futures index tracked by most VIX ETPs.

The data on SPX futures and VIX futures is tick-by-tick trade data registered with millisecond precision and obtained from TickData. Days where the exchanges closed earlier than 16:15

[3]The time of the daily VIX futures index settlement and end of VIX futures regular trading hours have later been changed to 16:00. Since the last date with settlement at 16:15 is October 23, 2020, the change took place after the end of our sample period.

Table 1: VIX exchanged-traded products.

Ticker	Name	Issuer	Leverage ratio	First day of trading	Last day of trading
VXX	iPath Series S&P 500 VIX Short Term Futures ETN	Barclays Bank	1	20090130	20190129
VXXB[a]	iPath Series B S&P 500 VIX Short Term Futures ETN	Barclays Bank	1	20180118	
VIXY	ProShares VIX Short-Term Futures ETF	ProShares	1	20110104	
VIIX	VelocityShares Daily Long VIX Short-Term ETN	Credit Suisse	1	20101130	20200702
VMAX	REX VolMAXX Long VIX Futures Strategy ETF	REX Shares	1	20160503	20180724
UVXY	ProShares Ultra VIX Short-Term Futures ETF	ProShares	2[b]	20111004	
TVIX	VelocityShares Daily 2x VIX Short-Term ETN	Credit Suisse	2	20101130	20200702
IVO	iPath Inverse S&P 500 VIX Short-Term Futures ETN	Barclays Bank	-1	20110114	20110916
IVOP	iPath Inverse S&P 500 VIX Short Term Futures ETN	Barclays Bank	-1	20110919	20180323
SVXY	ProShares Short VIX Short-Term Futures ETF	ProShares	-1[b]	20111004	
XIV	VelocityShares Daily Inverse VIX Short-Term ETN	Credit Suisse	-1	20101130	20180215
VMIN	REX VolMAXX Short VIX Futures Strategy ETF	REX Shares	-1	20160503	20181126

[a] As of May 2, 2019 VXXB took over the ticker VXX.
[b] As of February 28, 2018 the target leverage of UVXY was changed from 2 to 1.5 and for SVXY from -1 to -0.5.

are removed from the sample. We make the following modifications of the data: If a trade price is negative, we remove the trade. If more than one trade occurs for a given timestamp, we merge the trades into one with a trade price equal to the median price of the relevant trades.

Daily closing prices on VIX futures and the VIX index is retrieved from the CBOE homepage. From OptionMetrics we collect daily data on open interest and the Black-Scholes gamma of SPX options. Daily observations on the Assets Under Management (AUM) and prices of VIX ETPs are obtained from Bloomberg. Table 1 contains a list of the VIX ETPs included in our sample.

Intraday prices for a given time of the day are obtained as the price of the trade closest to that time. To measure intraday order flow, we follow Barbon et al. (2022) and compute the signed volume for the ith 1-minute interval on day t as

$$sVol_{i,t} = Vol_{i,t} 1_{\{r_{i,t}>0\}} - Vol_{i,t} 1_{\{r_{i,t}<0\}}, \tag{5}$$

where $Vol_{i,t}$ and $r_{i,t}$ is the trading volume and return over the ith interval on day t, respectively.

3.2 VIX ETPs and their rebalancing demand

The first VIX ETP was introduced in January 2009 and the products are designed to track a given VIX futures index. The most popular VIX ETPs track a VIX futures index with a target maturity of 30 days (short-term) but ETPs with longer target maturities also exist (mid-term). Since the goal of VIX ETPs is to provide investors with a volatility exposure that (before fees or other expenses) matches the daily performance of a VIX futures benchmark index, the issuers are exposed to the daily movements in the benchmark index. In order to hedge that exposure, issuers can hold a position in the underlying futures that enter the calculation of the benchmark index value. For the short-term VIX ETPs, issuers will hold a position in the front-month and second-month VIX futures. The composition of the VIX futures portfolio underlying the index changes daily. This is a consequence of the constant maturity of the index requiring a daily roll from contracts closer to maturity into contracts with longer time to maturity. If VIX ETP issuers wish to maintain their hedge, they must adjust their VIX futures position in response to these changes. Moveover, investors may invest or withdraw their investment from the product also feeding the need for adjusting the position in the underlying contracts. Finally, the leverage structure of the products can generate additional needs for modifying the underlying VIX futures hedge portfolio. All these factors contribute to the daily VIX futures rebalancing of VIX ETP issuers. We delegate the reader to Todorov (2021); Brøgger (2021) for further details and decomposition of the VIX ETP rebalancing demand.

While issuers of Exchange-Traded Funds (ETFs) are required to hold the securities from which the benchmark index is obtained, Exchange-Traded Notes (ETNs) are not. However, refraining from hedging involves a risk to the issuer. The issuers profit from fees and not from risk taking. According to Todorov (2021), anecdotal evidence indicates that both ETFs and ETNs hold the underlying VIX futures, and the estimates of the daily VIX futures demand matches the changes in the daily VIX futures holdings for the VIX ETPs that make their holdings public. Furthermore, since the indicative closing value of the benchmark index is based on prices at 16:15, issuers of VIX ETPs have an incentive to rebalance their VIX futures position as close as possible to the VIX futures market close (Alexander and Korovilas, 2013). For the

ETFs, whose performance evaluation is based on their tracking error, the best way for them to match the daily performance of the benchmark index is to trade at 16:15 prices. For the ETNs, the incentive to trade at 16:15 stems from the possibility of early redemption of ETN shares. If shares are redeemed, this is done at the daily closing indicative value which is computed from closing prices of VIX futures. Hence, for both ETFs and ETNs, issuers wishing to hedge therefore have a strong incentive to trade as close as possible to the market close.

3.3 Empirical strategy

Even if trading in VIX ETP shares has an informative component throughout the day, the corresponding rebalancing in VIX futures by VIX ETP issuers can be considered uninformed as this is postponed to the end of the day. This view is supported by studies showing how the rebalancing by VIX ETPs impacts the VIX futures market. Fernandez-Perez et al. (2019) show that the VIX futures market is less informationally efficient on days of large VIX ETP rebalancing flows especially leading up to market close where VIX ETPs are expected to implement most of their hedging. Brøgger (2021) documents a transitory price impact in the VIX futures market from rebalancing by VIX ETPs. Todorov (2021) finds a connection between the size of the non-fundamental component in VIX futures prices and VIX ETP rebalancing.

To understand if VIX futures market makers hedging activities move the SPX futures market through a non-informational channel, our empirical strategy relies on the identification of such uninformed VIX futures trading from the VIX ETP demand. When VIX futures market makers trade with counterparties whose VIX futures demand is uninformed, we believe that their hedging activities are more likely to generate a SPX futures price impact unrelated with price discovery. Besides the uninformed nature, the benefits of using the VIX ETP demand is that its size can be estimated reliably and that we know when it is implemented. Thus, we have a proxy for the SPX futures trading by VIX futures dealers but also know when to look for a price impact in the SPX futures market. As the proxy for the SPX futures demand by VIX futures market makers, we use the VIX futures demand by VIX ETPs measured as the sum of the number of front-month and second-month contracts. This is reasonable since the number of VIX futures contracts demanded is the main component determining how many SPX futures contracts dealers must trade in order to hedge.

Given that VIX ETPs should ideally trade at the VIX futures market close, i.e. at 16:15, we look for a price impact over the 10 minutes interval leading up to this, namely from 16:05 to 16:15. Analyzing the impact of VIX ETPs on VIX futures, Brøgger (2021) considers VIX ETPs to be rebalancing over the interval 15:30-16:15. O'Neill and Whaley (2021) use 16:00-16:15 and also find that VIX ETPs' impact on VIX futures is robust to the use of wider intervals but with weaker explanatory power. We choose the more narrow window up to the VIX futures market close because trading in the SPX futures market around 16:00 can be largely driven by motives unrelated to VIX futures hedging. We confirm this in Section 4.1.

For analyzing the price impact, we measure the VIX ETP demand at 16:00. Hence, our proxy for the SPX futures trading by dealers is measured at 16:00 while we look for a price impact over 16:05-16:15. The measurement is done at 16:00 for two reasons: First, using a time point inside the 10 minute rebalancing window, we would encounter simultaneity issues. Second, the AUM of VIX ETPs reported by Bloomberg is recorded at 16:00.

In order to connect the VIX ETP demand with the SPX futures trading by VIX futures market makers, we rely on the following simplifying assumptions: VIX futures market makers are on the other side of each VIX futures trade, including the trades initiated by VIX ETP issuers. We ignore the effect of rebalancing of an existing VIX futures position due to a change in market conditions, but only focus on the impact from hedging the change in the net position experienced by dealers. We also assume that over the time-frame 16:05-16:15, the aggregate net position change of dealers is largely reflected by the negative of the VIX ETP demand. This simplification appears to be justified empirically in Section 4.1. The incentive of VIX ETPs to trade VIX futures in the minutes leading up to 16:15 means that the net position change of dealers takes place just before market close. At the end of the day, dealers are likely to want a fully hedged position (Baltussen et al., 2021). Hence, when the dealers' net position in VIX futures change towards the end of the day, they turn to the SPX futures market to hedge away the corresponding risk before the market close at 16.15. Hence, we look for effects of hedging on the SPX futures market over the same interval as VIX ETPs are assumed to do their VIX futures trading.

Following these assumptions, we expect that ex-ante measures of VIX futures market makers hedging activities predict SPX futures returns over 16:05-16:15, and are in the direction consistent with the hedging strategy.

To account for other factors influencing the SPX futures end-of-day return, we control for the SPX futures return, $r^{ES}_{t,09:30-16:05}$, and VIX futures index return, $r^{\overline{VX}}_{t,09:30-16:05}$, computed up to the time where rebalancing is assumed to begin. These variables allow for the continuation or reversal of a trend throughout the remainder of the trading day and are thus related to market efficiency. We also control for the SPX futures volume up to 16:05, $Vol^{ES}_{t,09:30-16:05}$, the level of the VIX index, VIX_t, using its closing value which is measured at 16:15. In order to separate a price impact due to hedging activities from a possible price change stemming from a volatility feedback channel, we control for the realized volatility of the SPX futures over the rebalancing window, $RV^{ES}_{t,16:05-16:15}$. The realized volatility is computed as the square root of the sum of squared 1-minute log returns for the relevant part of the day.

As mentioned above, dealers are assumed to postpone most of their hedging to the end of the trading day. In the presence of VIX futures hedging, late-day SPX futures returns could therefore be driven by dealers hedging the change in their VIX futures exposure accumulated over the entire trading day. If dealers' net position change accumulated up to 16:05 is correlated with the net position change induced by the VIX ETP rebalancing, we may falsely conclude that the demand of VIX ETPs is driving SPX futures returns. In order to separate the impact of dealers hedging the VIX futures exposure accumulated up to 16:05 and the VIX futures trading by VIX ETPs implemented after 16:05, we control for a proxy of the aggregate VIX futures demand until 16:05, $sVol^{VX}_{t,09:30-16:05}$. The proxy is constructed as the sum of the signed 1-minute volume of front-month and second-month VIX futures over the interval from 09:30 to 16:05. The variable is similar to the VIX ETP demand variable in the way that if we change the sign of the variable, we proxy the net position change of dealers. If dealers use the last 10 minutes before market close to hedge their net position change accumulated up to 16:05, we would expect to see a significantly negative coefficient on this variable.

3.4 Estimating the VIX ETP rebalancing demand

We follow the methodology of Todorov (2021) to estimate the aggregate demand for VIX futures among VIX ETPs. The VIX ETPs that use the first two VIX futures contracts as the main hedging vehicle track a 30-day constant maturity VIX futures index. We use $T^{\overline{VX}}$ to denote the target maturity of the benchmark index. Hence, $T^{\overline{VX}} = 30$ calendar days for the VIX ETPs in our sample (see Table 1). The weights in the front-month and second-month contracts are chosen to maintain the target maturity, and we compute the weights in accordance with the methodology of the SPVXSTR index (see S&P Dow Jones Indices (2021)). To denote the weight in the front-month contract, we use ω_t. VIX ETPs are also characterized by their leverage target, which we denote by L. L is 1 when the VIX ETP simply tracks the given VIX futures index while it is 2 when they track twice the index return and -1 when tracking the inverse index return. The front-month and second-month VIX futures dollar demand of a given VIX ETP can be computed as

$$\begin{aligned} Demand_t^{\$,VX1} =& -\frac{L}{T^{\overline{VX}}} A_{t-1}\left(1+Lr_t^{\overline{VX}}\right) + \omega_{t-1}A_{t-1}L(L-1)\,r_t^{\overline{VX}} \\ &+ \left(\omega_{t-1} - \frac{1}{T^{\overline{VX}}}\right) Lu_t + \omega_{t-1}(1-\hat{\omega}_{t-1})LA_{t-1}\left(r_t^{VX2} - r_t^{VX1}\right) \end{aligned} \tag{6}$$

$$\begin{aligned} Demand_t^{\$,VX2} =& \frac{L}{T^{\overline{VX}}} A_{t-1}\left(1+Lr_t^{\overline{VX}}\right) + (1-\omega_{t-1})A_{t-1}L(L-1)\,r_t^{\overline{VX}} \\ &+ \left(1-\omega_{t-1} + \frac{1}{T^{\overline{VX}}}\right) Lu_t - \hat{\omega}_{t-1}(1-\omega_{t-1})LA_{t-1}\left(r_t^{VX2} - r_t^{VX1}\right) \end{aligned} \tag{7}$$

where A_t is AUM of the VIX ETP, and u_t denotes the dollar-value of capital flows defined as $u_t = A_t - (1+r_t)A_{t-1}$ with r_t denoting the return on the VIX ETP based on the price of its shares. We also denote the value of the front-month VIX futures position relative to the total value of the VIX futures position by $\hat{\omega}_t = \omega_t P_t^{VX1}/(\omega_t P_t^{VX1} + (1-\omega_t)P_t^{VX2})$ with P_t^{VXm} denoting the VIX futures price for $m = 1, 2$. Finally, r_t^{VXm} is the return on the mth VIX futures contract, and the return of the VIX futures benchmark index is given by

$$r_t^{\overline{VX}} = \hat{\omega}_{t-1} r_t^{VX1} + (1 - \hat{\omega}_{t-1})\, r_t^{VX2}. \tag{8}$$

The total demand for each of the two contracts on date t is the sum over each of the J VIX ETP's demand, $Demand_t^{\$,VXm,total} = \sum_{j=1}^{J} Demand_t^{\$,VXm,j}$. For each t, we combine the VIX futures demand for the two contracts into a single number, $D_t^{VIX\,ETP}$, corresponding to the sum of the number of VX1 and VX2 contracts demanded by VIX ETPs

$$D_t^{VIX\,ETP} = \frac{Demand_t^{\$,VX1,total}}{cP_t^{VX1}} + \frac{Demand_t^{\$,VX2,total}}{cP_t^{VX2}}, \tag{9}$$

where c denotes the contract multiplier of the VIX futures contract. This variable is our proxy for the VIX futures market makers' hedging activities in SPX futures.

3.5 Descriptive statistics

Figure 3 depicts the estimated daily VIX futures demand by VIX ETP issuers. The upper panel shows the demand split on the front-month and second-month contracts, and the lower panel shows the sum of the two as defined in equation (9). The largest number of contracts that VIX ETPs should buy corresponds to the volmaggedon event of February 5, 2018.

Panel A of Table 2 shows descriptive statistics of the VIX ETP demand accumulated from the market close at 16:15 on day $t-1$ up to 16:15 on day t as well as the demand used for the predictive analysis which is accumulated only up to 16:00 on day t. We let $D_t^{VIX\,ETP-} = \min\left\{D_t^{VIX\,ETP}, 0\right\}$ and $D_t^{VIX\,ETP+} = \max\left\{D_t^{VIX\,ETP}, 0\right\}$ denote the VIX ETP demand when negative and positive, respectively. Both $D_t^{VIX\,ETP-}$ and $D_t^{VIX\,ETP+}$ appear to have similar distributions with median and lower and upper quartiles of similar magnitudes.

Panel B of Table 2 reports descriptives of the control variables listed in Section 3.3. Most of the correlations among the control variables displayed in Table 3 have the expected sign: The level of the VIX index and the SPX futures realized volatility have a strong positive correlation,

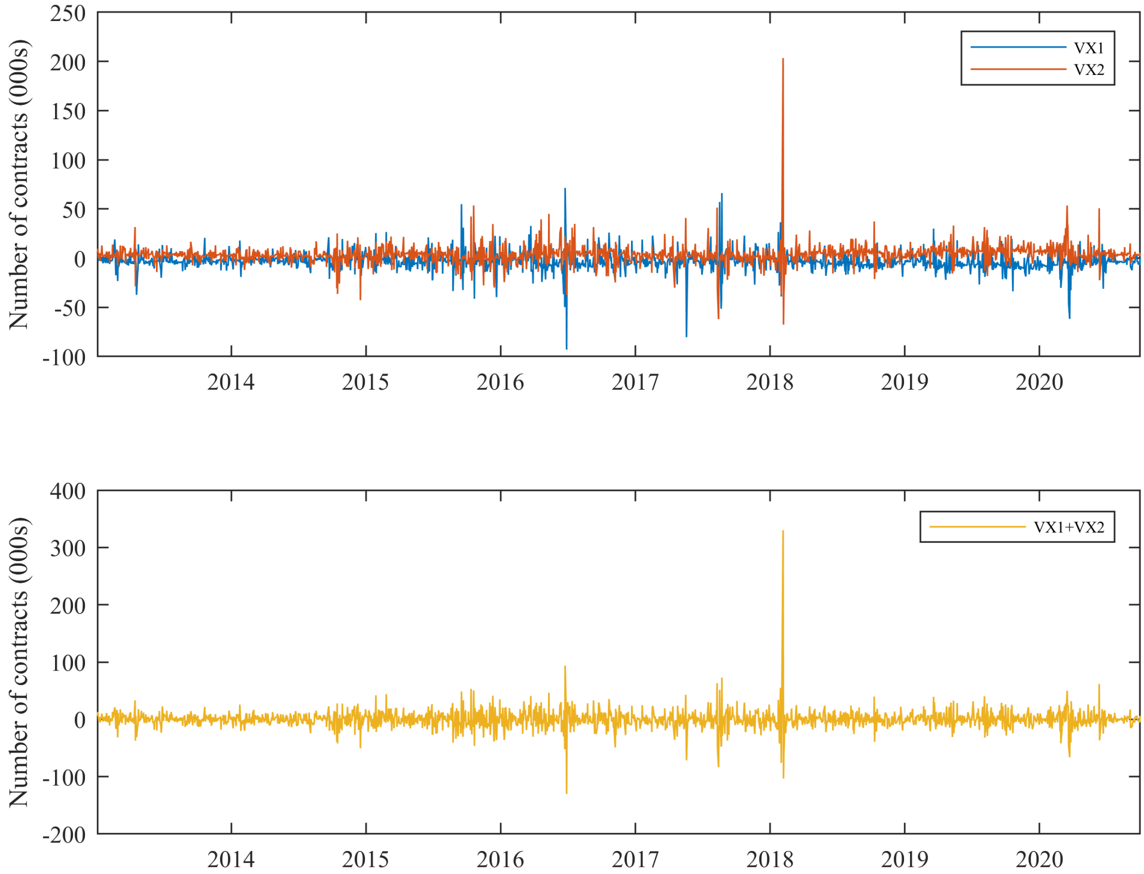

Figure 3: VIX futures rebalancing demand by VIX ETP issuers. The rebalancing demand is measured in number of contracts over 16:15 on day $t-1$ to 16:15 on day t. The lower panel shows the sum of the demand of the front-month and second-month VIX futures as defined in equation (9), while the upper panel shows the demand for each of the two contracts corresponding to the two terms in (9).

VIX futures returns are positively correlated with signed VIX futures volume, and SPX futures returns are negatively correlated with VIX futures returns.

4 The impact of end-of-day VIX futures trading

In this section, we present the empirical results on the connection between the VIX futures rebalancing demand by VIX ETPs the SPX futures market at the end of the trading day. Section 4.1 analyzes volume and return patterns conditional on the VIX ETP rebalancing demand over the trading day. The results from predicting end-of-day SPX futures returns in-sample are shown in Section 4.2 while Section 4.3 studies the performance out-of-sample. In Section 4.4,

Table 2: Descriptive statistics. The VIX ETP demand is measured in number of contracts (in thousand) over 16:15 on day $t-1$ to 16:00 or 16:15 on day t. Returns are in percentages. SPX futures volume and VIX futures signed volume are measured in thousand.

	Mean	Std. dev.	Min	Q1	Median	Q3	Max
Panel A: VIX ETP demand variables							
$D^{VIXETP}_{t,16:15}$	0.279	15.996	-130.236	-6.231	0.019	6.945	330.134
$D^{VIXETP}_{t,16:00}$	0.359	15.728	-145.225	-5.858	0.173	6.699	340.479
$D^{VIXETP-}_{t,16:00}$	-9.112	10.992	-145.225	-11.356	-6.037	-2.785	-0.011
$D^{VIXETP+}_{t,16:00}$	9.483	14.131	0.024	2.932	6.515	11.965	340.479
Panel B: Control variables							
$r^{ES}_{t,09:30-16:05}$	0.020	0.753	-5.602	-0.257	0.059	0.379	4.328
$r^{\overline{VX}}_{t,09:30-16:05}$	-0.161	3.367	-20.404	-1.831	-0.375	1.269	35.882
$Vol^{ES}_{t,09:30-16:05}$	1262.841	458.686	274.103	945.500	1171.513	1472.492	3929.666
VIX_t	16.379	7.274	9.140	12.620	14.170	17.320	82.690
$sVol^{VX}_{t,09:30-16:05}$	0.309	10.544	-53.553	-5.284	-0.017	5.019	95.409
$RV^{ES}_{t,16:05-16:15}$	0.106	0.104	0.020	0.062	0.084	0.116	1.823

Table 3: Correlation of control variables.

	$r^{ES}_{t,09:30-16:05}$	$r^{\overline{VX}}_{t,09:30-16:05}$	$Vol^{ES}_{t,09:30-16:05}$	VIX_t	$sVol^{VX}_{t,09:30-16:05}$	$RV^{ES}_{t,16:05-16:15}$
$r^{ES}_{t,09:30-16:05}$	1.000					
$r^{\overline{VX}}_{t,09:30-16:05}$	-0.733	1.000				
$Vol^{ES}_{t,09:30-16:05}$	-0.231	0.263	1.000			
VIX_t	-0.113	0.118	0.457	1.000		
$sVol^{VX}_{t,09:30-16:05}$	-0.562	0.749	0.215	0.066	1.000	
$RV^{ES}_{t,16:05-16:15}$	-0.192	0.184	0.509	0.788	0.138	1.000

we analyze how to exploit the documented predictability through trading strategies. Finally, Section 4.5 tests for a subsequent reversal in the SPX futures price from market close up to 10:00 the following trading day.

4.1 Intraday volume and return patterns

As a preliminary analysis, Figure 4 shows the average intraday trading volume of VIX futures and SPX futures for deciles of the absolute number of front-month and second-month VIX futures contracts demanded by VIX ETPs. On days of large VIX ETP rebalancing needs in either direction, the upper panel shows that the VIX futures volume is generally higher during the entire day. This makes sense as movements in the VIX futures market directly drive the VIX

ETP rebalancing demand as shown in (6) and (7). A possible explanation for the extreme spike in volume in the final minutes up to 16:15 is the rebalancing by VIX ETPs up to market close. The spike in volume is increasing with the absolute number of VIX futures contracts that VIX ETPs demand. Focusing on the panel showing the average trading volume in the SPX futures, we observe a spike in trading around 16:00. Possibly, the increased amount of trading in SPX futures at this time point has to do with rebalancing of SPX option dealers' hedges, rebalancing by issuers of leveraged ETFs tracking stock market indices, and in general different investors executing trades before the end of the day (Cheng and Madhavan, 2010; Baltussen et al., 2021). However, we are interested in the spike at the very end of the timeline as this coincides with the increased amount of trading in the VIX futures market. We observe that within the last 5 minutes there is much higher SPX futures trading volume for days with large VIX ETP rebalancing. This pattern can be explained by the VIX futures hedging mechanisms: The VIX ETP rebalancing is implemented in the window leading up to 16:15 and changes the exposure of VIX futures market makers which forces them to rebalance in SPX futures.

We also take a further look at the direction of trading by analyzing the signed trading volume. Figure 5 shows the average signed volume for the two futures markets from 15:30 to 16:15 for deciles of the VIX ETP rebalancing demand. The upper panel shows that the subsample of days where VIX ETPs should buy the most VIX futures coincide with the highest average VIX futures buying just before 16:15. Furthermore, signed volume is slightly higher over the entire rebalancing window for the 10th decile suggesting how some of the rebalancing is implemented gradually up to market close, albeit with the majority implemented within the last few minutes of trading. The reverse pattern applies for the lower deciles corresponding to days where VIX ETPs should sell the most VIX futures. This indicates how VIX ETP demand is an important driver of net buying in VIX futures at the end of regular trading hours. Turning to the SPX futures depicted in the lower panel of Figure 5, we see that for a given decile, this market experiences net buying in roughly the opposite direction of the VIX futures. In particular, the SPX futures selling observed on days where VIX ETPs do the most VIX futures buying matches the direction of SPX futures trading prescribed by the VIX futures hedging strategy.

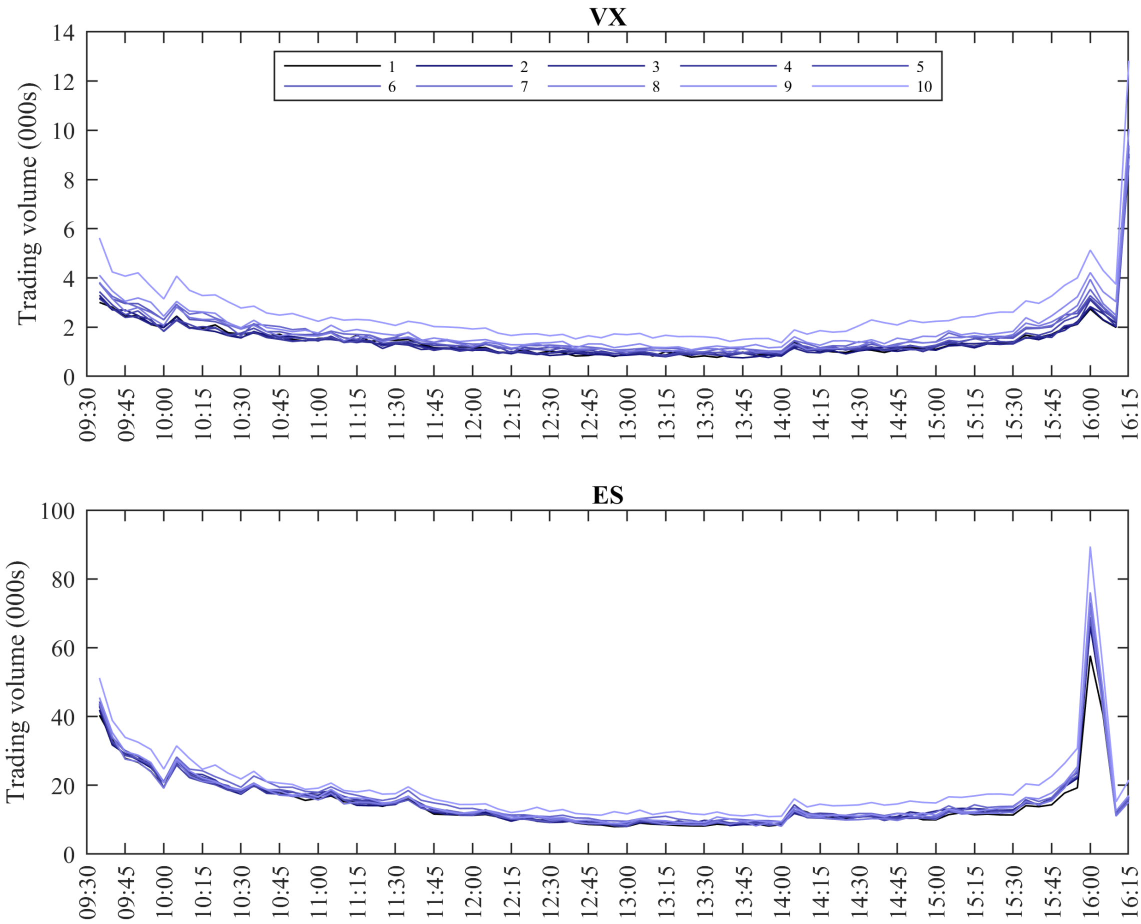

Figure 4: Intraday VIX futures and SPX futures trading volume. For each 5-minute interval, the average trading volume is computed within each subsample constructed from the deciles of VIX ETP rebalancing demand. The rebalancing demand is measured as the absolute number of VX1 and VX2 contracts and over 16:15 on day $t-1$ to 16:15 on day t. The VIX futures volume is the sum of the volume of VX1 and VX2. The SPX futures volume is the volume of the contract closest to expiration except when this is less than six days.

We note that the SPX futures signed volume displays some fluctuations around 16:00. As mentioned above, this is likely driven by the presence of traders with various motives related to the close of the general stock market. Moreover, no clear pattern emerges in signed volume across the deciles of VIX ETP demand around 16:00.

Next, the cumulative return of the SPX futures conditional on the VIX ETP demand is shown in Figure 6. Focusing on the 9th and 10th decile, we see that on days where VIX ETPs buy the most VIX futures, negative returns begin to materialize in the SPX futures market after 15:30. This is consistent with how large rebalancing demand may lead VIX ETPs to begin rebalancing earlier in order to mitigate fill risk (Shum et al., 2016). In the minutes after 16:00,

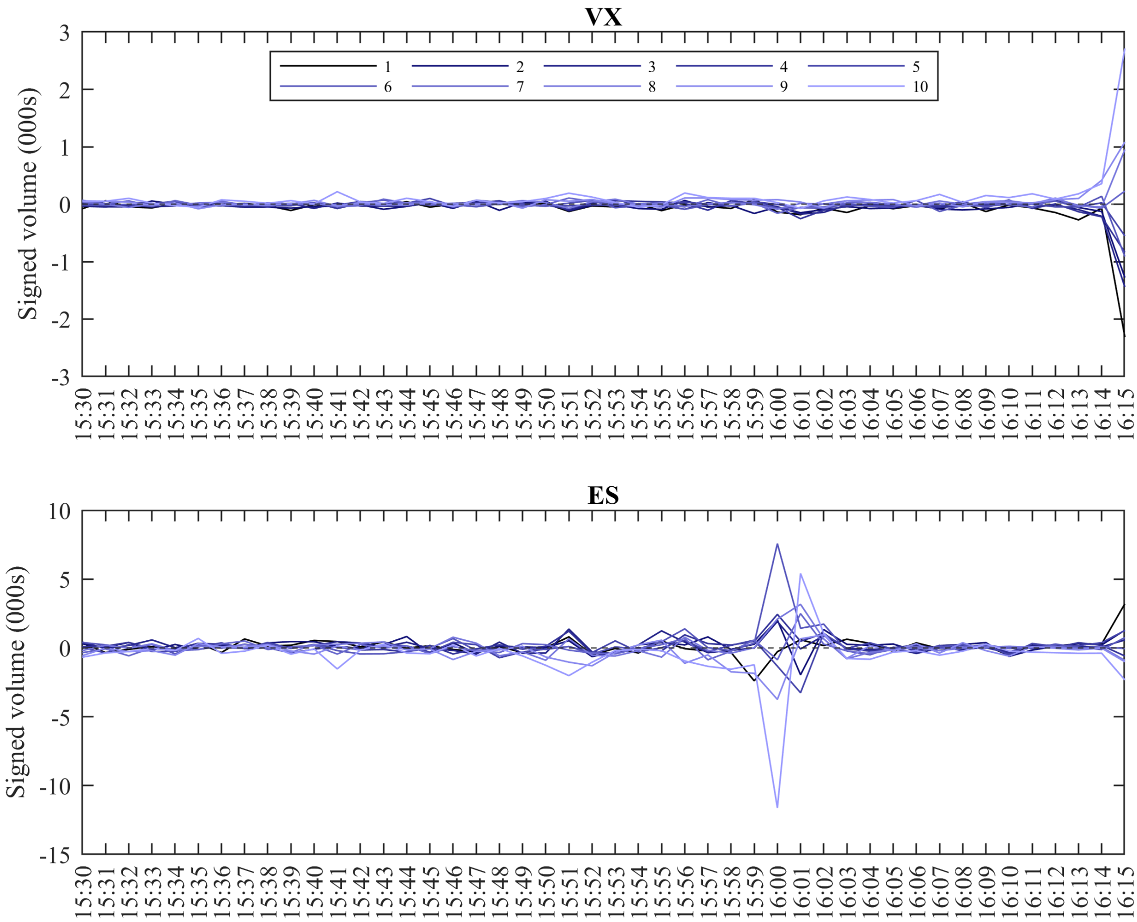

Figure 5: Intraday VIX futures and SPX futures signed volume. Average signed volume based on (5) over each 1-minute interval with average computed within each subsample constructed from the deciles of the VIX ETP rebalancing demand. The rebalancing demand is measured as the sum of the number of VX1 and VX2 contracts and over 16:15 on day $t-1$ to 16:15 on day t. The VIX futures signed volume is the sum of the signed volume of VX1 and VX2.

returns exhibit a steady decline until market close with a further downward shift in prices in the very last minute of trading. As we move down the deciles, reflecting more VIX futures selling, there is a tendency for the cumulative return to be positive. However, the impact on returns for the lower deciles appears to be less severe. Again these observations are supportive of the presence of VIX futures dealers hedging the VIX ETP driven exposure in the SPX futures market, and that the hedging activities impact SPX futures prices asymmetrically depending on the sign of the VIX ETP demand.

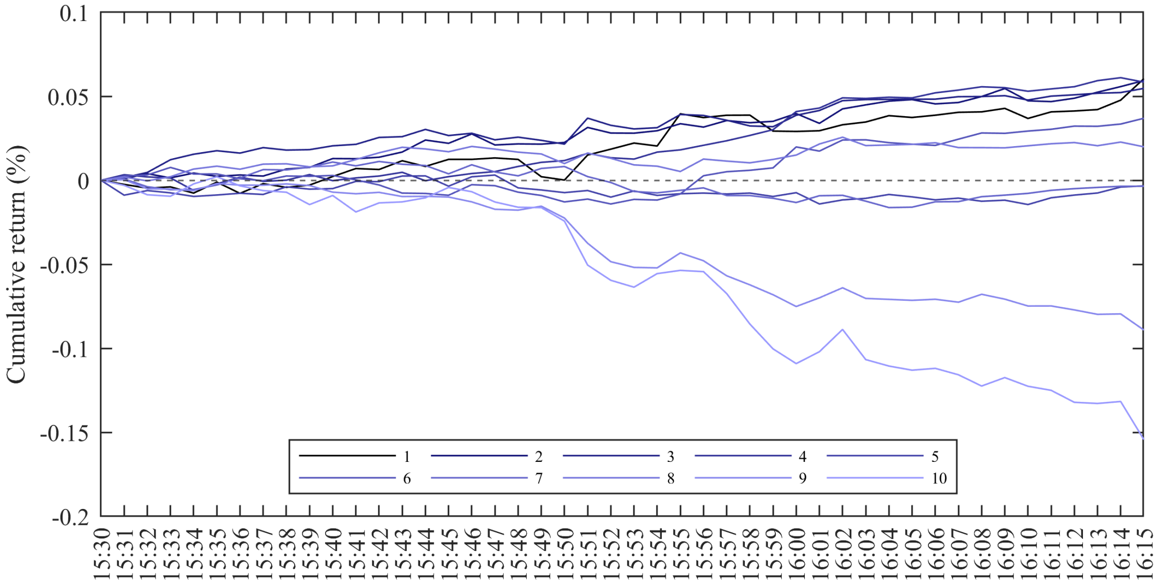

Figure 6: SPX futures cumulative return. Average cumulative return with average computed within each subsample constructed from the deciles of the VIX ETP rebalancing demand. The rebalancing demand is measured as the sum of the number of VX1 and VX2 contracts and over 16:15 on day $t-1$ to 16:15 on day t.

4.2 Price impact

With an estimate of the amount of uninformed VIX futures trading taking place prior to market close, we can examine the effect of uninformed VIX futures trading on the SPX futures market during this part of the day. Thus, we analyze to which extent the VIX ETP rebalancing demand measured at 16:00 can explain SPX futures returns, $r^{ES}_{t,16:05-16:15}$, over the rebalancing window using the following regression model

$$r^{ES}_{t,16:05-16:15} = \alpha + \beta D^{VIX\,ETP}_t + u_t, \tag{10}$$

where the variable $D^{VIX\,ETP}_t$ is as in (9). Given the discussion in Section 4.1, we let the rebalancing window start at 16:05 (as opposed to 16:00) in order to limit the SPX futures trading related to other activities. If β is significantly negative, buying in VIX futures depresses SPX futures returns. Such an effect would be consistent with the hedging mechanisms illustrated in Figure 2 as the VIX ETPs' VIX futures buying is hedged by selling SPX futures. Since the VIX futures buying in this time window is mechanically driven by rebalancing needs rather

Table 4: SPX futures return over the VIX ETP rebalancing window. The table reports the regression results for the model in equation (10) with all variables standardized. $D_t^{VIX\,ETP}$ is the VIX ETP rebalancing demand measured at 16:00, and $r_{t,09:30-16:05}^{ES}$ and $r_{t,09:30-16:05}^{\overline{VX}}$ are the returns on the SPX futures contract and the VIX futures short-term index, respectively, up to the beginning of the rebalancing window. $Vol_{t,09:30-16:05}^{ES}$ is the SPX futures volume up to the rebalancing window. VIX_t denotes the level of the VIX index, $RV_{t,16:05-16:15}^{ES}$ is the SPX futures realized volatility over the rebalancing window, and $sVol_{t,09:30-16:05}^{VX}$ is the VIX futures signed volume up to the beginning of the rebalancing window on day t. Newey-West t-statistics are in parentheses. ***, **, * indicates 1%, 5% and 10% significance, respectively.

$r_{t,16:05-16:15}^{ES}$	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$D_t^{VIX\,ETP}$	-0.213***	-0.178***	-0.206***	-0.211***	-0.201***	-0.199***	-0.184***
	(-5.146)	(-3.204)	(-5.158)	(-5.162)	(-4.406)	(-4.821)	(-3.397)
$r_{t,09:30-16:05}^{ES}$		-0.082					-0.103
		(-1.030)					(-1.216)
$r_{t,09:30-16:05}^{\overline{VX}}$		-0.120					-0.111
		(-1.199)					(-0.943)
$Vol_{t,09:30-16:05}^{ES}$			-0.126***				-0.086**
			(-2.783)				(-2.053)
VIX_t				-0.075			0.094
				(-1.373)			(1.435)
$sVol_{t,09:30-16:05}^{VX}$					-0.025		0.027
					(-0.854)		(0.636)
$RV_{t,16:05-16:15}^{ES}$						-0.132*	-0.167
						(-1.655)	(-1.532)
Adj. R^2 (%)	4.47	4.92	6.00	4.99	4.47	6.14	7.20
No. of Obs.	1932	1932	1932	1932	1932	1932	1932

than driven by the arrival of new information, this indicates (at least during the rebalancing window) that VIX futures hedging makes the SPX futures market less informational efficient.

Table 4 shows that the VIX ETP rebalancing demand negatively predicts SPX futures returns over the last 10 minutes leading up to market close. When VIX ETP rebalancing involves buying more VIX futures, then on average the SPX futures return decreases. This is what would be expected under price pressures from VIX futures hedging activities and indicates that these trades can move the SPX futures market. The size of the coefficient on the VIX ETP demand appears to be stable and maintains a significance level below 1% as we vary the set of control variables. We observe that among the control variables, only the SPX futures volume turns out significant in the full regression reported in column (7), and indicates that an increase in the SPX futures volume before 16:05 is expected to result in a decline in returns over the following 10 minutes and vice versa. Also, the values of the adjusted R-squared are above 4.47% in all the considered regressions. This level of R-squared is remarkable and above what is found in other studies on intraday market returns such as Baltussen et al. (2021); Gao et al. (2018).

4.2.1 Asymmetric price impact

Motivated by the discussion in Section 2, we allow for the VIX ETP demand to have a different impact on the end-of-day SPX futures returns depending on whether VIX ETP issuers buy or sell VIX futures. Using the negative and positive part of the VIX ETP demand, we estimate the model

$$r^{ES}_{t,16:05-16:15} = \alpha + \beta_1 D_t^{VIX\,ETP-} + \beta_2 D_t^{VIX\,ETP+} + u_t. \tag{11}$$

Under the VIX futures hedging activities we would expect that β_2 is negative as VIX futures buying translates into as short position of the dealer which is hedged by selling SPX futures. Furthermore, the risk of a feedback effect from VIX ETPs buying VIX futures, indicates that this case involves a greater likelihood of a more severe impact on SPX futures from the VIX futures hedging activities. Conversely, given the hedging strategy's weaker implications on how VIX futures market makers should trade SPX futures following VIX futures selling, we have no strong prior beliefs about the sign of β_1.

The results are given in Panel A of Table 5 and show that on average only VIX futures buying by VIX ETPs significantly predicts SPX futures returns. In fact, the positive part of the VIX ETP demand is highly significant with a t-statistic of -8.76, and the negative coefficient is in line with the direction of the price impact from dealers' hedging activities. Conversely, the coefficient on the VIX ETP demand for days where it is negative remains insignificant across all the different sets of control variables used. These are they days where we cannot say how dealers are expected to trade SPX futures. The results are supportive of an asymmetric price impact from VIX futures hedging where the situation with dealers hedging a short VIX futures position seems to be driving the impact. The adjusted R-squared of the model with no additional control variables attains a value of 5.99% stressing the importance of the VIX ETP demand in explaining end-of-day returns. After including all the control variables, we reach a level of 7.78%. Both of these adjusted R-squared are higher than those obtained from the baseline regression model in equation (10) emphasizing the advantage of incorporating asymmetry.

4.2.2 Non-linear price impact

To account for a potential non-linear impact of the hedging activities, we include the squared VIX ETP demand multiplied by the variable, s_t, which is equal to one (negative one) when VIX ETP demand is positive (negative). The regression model is

$$r^{ES}_{t,16:05-16:15} = \alpha + \beta_1 D_t^{VIX\,ETP} + \beta_2 (D_t^{VIX\,ETP})^2 \cdot s_t + u_t. \quad (12)$$

The estimated parameters are given in Panel B of Table 5. While the linear term indicates that VIX ETP demand negatively predicts SPX futures returns, the non-linear term reveals that the negative predictive relation is even stronger in the tails of the distribution of the VIX ETP demand. This means that when hedging activities are more pronounced there is on average a larger impact on the SPX futures market. Similar to the model including an asymmetric price impact, we achieve a higher adjusted R-squared relative to the baseline model when taking into account non-linear price impact.

4.2.3 Price impact under option rebalancing

Besides VIX futures hedging, there may also be other factors driving SPX futures returns over the VIX ETP rebalancing window. For instance, SPX option dealers may simultaneously hedge their exposure in the SPX futures market. In particular, if the aggregate gamma position of dealers is positive, the rebalancing by option dealers has a stabilizing effect as they trade against the market movements. These mechanisms could therefore limit the impact of VIX futures hedging on the SPX futures price. On the other hand, a negative net gamma position would amplify the SPX futures price movements initiated by VIX futures hedging activities as option market makers rebalance by trading in the direction of the market movements.

In order to analyze the impact of the VIX futures hedging under simultaneous rebalancing by option market makers, we estimate the daily aggregate net gamma position of option dealers. This is done along the lines of Baltussen et al. (2021); Barbon and Buraschi (2021) by using SPX options data from OptionMetrics and making some assumptions: End-user demand is long in put options and short in call options. As explained in Section 2, this claim is empirically justified. Second, we assume that the option dealer is the counterparty in all option trades, and finally that the dealers delta hedge their exposure. Based on these assumptions, we proxy the net gamma position at time t by

$$NGP_t = \sum_{i=1}^{N_t^C} \Gamma_t^{BS}(C^i) OI_t(C^i) - \sum_{i=1}^{N_t^P} \Gamma_t^{BS}(P^i) OI_t(P^i), \tag{13}$$

where N_t^C is the number of call options traded at time t with an open interest greater than zero. $\Gamma_t^{BS}(C^i)$ denotes the Black-Scholes gamma of call option i, and $OI_t(C^i)$ is the option's open interest. Similar notation holds for put options.

Motivated by this, we decompose the net gamma position into a positive and negative part, NGP^+ and NGP^-, and introduce the following two variables: The first equals the product of the VIX ETP demand and one minus the negative part of the net gamma position, $D_t^{VIX\,ETP} \cdot (1 - NGP_t^-)$. This variable takes into account the amplifying feature a negative gamma position by scaling the size of the VIX ETP demand. We subtract the net gamma position from one, as directly multiplying the VIX ETP demand with the net gamma position would neglect a possible impact from the VIX ETP demand when the gamma position equals zero. The second variable equals the product of the VIX ETP demand and the exponential of the positive part of the net gamma position multiplied by negative one, $D_t^{VIX\,ETP} \cdot e^{-NGP_t^+}$. This means that when the net gamma position increases, we scale the VIX ETP demand by a positive number below zero. In this way, any price pressures from the VIX futures hedging is damped when the net gamma position is positive and more so when it increases in value. Hence, we attempt to capture a situation where a positive and increasing net gamma position would imply a progressively stronger dampening effect, leaving less room for the VIX ETP demand to impact SPX futures returns. Due to the non-linear transformation of NGP^+, we normalize the time series NGP_t to have unit variance before we split the variable into its negative and positive part. Using these two variables as regressors, we examine the effect of the uninformed VIX ETP rebalancing demand while incorporating the effect of the net gamma position by the following regression

$$r^{ES}_{t,16:05-16:15} = \alpha + \beta_1 D_t^{VIX\,ETP} \cdot (1 - NGP_t^-) + \beta_2 D_t^{VIX\,ETP} \cdot e^{-NGP_t^+} + u_t. \tag{14}$$

In this regression model, a price impact implied by the VIX futures hedging strategy is aligned with a negative value of β_1 and β_2, albeit the latter effect might be more difficult to detect due to the dampening feature of a positive gamma position. We note here that the gamma position is measured at 16:00 on date t. Hence, we still do not encounter simultaneity issues when predicting returns over 16:05-16:15.

Panel C of Table 5 shows the results from running the regression in (14). The negative coefficient on the product between VIX ETP demand and the negative part of the net gamma position is consistent with a price impact from VIX futures hedging. The coefficient corresponding to the positive gamma position is significantly different from zero for most of the regressions but at a lower significance level. Hence, the result are in line with the stabilizing feature of a aggregate positive gamma position of dealers.

4.3 Out-of-sample predictive performance

Motivated by the promising predictive in-sample performance of the VIX ETP demand on the end-of-the-day SPX futures return, we devote this section to study the out-of-sample performance. Similar to Campbell and Thompson (2008); Welch and Goyal (2008), we benchmark the performance against a random walk with drift equal to the historical average of the end-of-the-day returns. Hence, we compute the out-of-sample R-squared as

Table 5: SPX futures return over the VIX ETP rebalancing window. Panel A contains the estimates from equation (11), Panel B shows estimation results from equation (12), and Panel C from equation (14). Each column reports the results using different sets of control variables. The variables have been standardized. Newey-West t-statistics are in parentheses. ***, **, * indicates 1%, 5% and 10% significance, respectively.

$r^{ES}_{t,16:05-16:15}$	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Controls	None	$r^{ES}_{t,09:30-16:05}$ $r^{VX}_{t,09:30-16:05}$	$Vol^{ES}_{t,09:30-16:05}$	VIX_t	$sVol^{VX}_{t,09:30-16:05}$	$RV^{ES}_{t,16:05-16:15}$	All
Panel A: Asymmetric impact							
$D^{VIXETP-}_t$	-0.015	0.000	-0.034	-0.022	-0.010	-0.032	-0.035
	(-0.395)	(0.001)	(-0.951)	(-0.636)	(-0.251)	(-0.986)	(-0.899)
$D^{VIXETP+}_t$	-0.243***	-0.220***	-0.220***	-0.235***	-0.236***	-0.214***	-0.193***
	(-8.760)	(-6.100)	(-7.232)	(-8.399)	(-8.104)	(-6.511)	(-4.550)
Adj. R^2 (%)	5.99	6.36	6.88	6.22	5.97	6.96	7.78
No. of Obs.	1932	1932	1932	1932	1932	1932	1932
Panel B: Non-linear impact							
D^{VIXETP}_t	-0.132***	-0.095	-0.132***	-0.133***	-0.118**	-0.130***	-0.118*
	(-2.576)	(-1.373)	(-2.651)	(-2.642)	(-1.986)	(-2.620)	(-1.852)
$(D^{VIXETP}_t)^2 \times s_t$	-0.123***	-0.122***	-0.115***	-0.119***	-0.125***	-0.107***	-0.098***
	(-4.555)	(-4.657)	(-4.536)	(-4.571)	(-4.518)	(-4.617)	(-4.162)
Adj. R^2 (%)	5.30	5.72	6.70	5.75	5.31	6.74	7.69
No. of Obs.	1932	1932	1932	1932	1932	1932	1932
Panel C: Gamma exposure interaction							
$D^{VIXETP}_t(1-NGP^-_t)$	-0.223***	-0.190***	-0.212***	-0.218***	-0.209***	-0.204***	-0.182***
	(-5.385)	(-3.437)	(-5.040)	(-5.148)	(-4.314)	(-4.281)	(-3.124)
$D^{VIXETP}_t e^{-NGP^+_t}$	-0.036**	-0.026	-0.041***	-0.036**	-0.033**	-0.036**	-0.033**
	(-2.367)	(-1.596)	(-2.779)	(-2.395)	(-2.083)	(-2.379)	(-2.104)
Adj. R^2 (%)	4.99	5.73	6.36	5.40	5.05	6.37	7.60
No. of Obs.	1928	1928	1928	1928	1928	1928	1928

$$R^2_{OOS} = 1 - \frac{\sum_{t=1}^{T}\left(r^{ES}_{t,16:05-16:15} - \hat{r}^{ES}_{t,16:05-16:15}\right)^2}{\sum_{t=1}^{T}\left(r^{ES}_{t,16:05-16:15} - \bar{r}^{ES}_{t,16:05-16:15}\right)^2} \tag{15}$$

where r^{ES}_t is the actual return, $\hat{r}^{ES}_t$ is the predicted return from the regression model estimated using observations up to time $t-1$ (expanding window) , and $\bar{r}^{ES}_t$ is the historical average return based on observations up to time $t-1$. T is the total number of sample dates excluding the observations within the first year of the sample used for the initial estimation. In this way, forecasts from the model are evaluated relative to the historical average of returns, and a positive value means that the proposed model produces superior forecasts.

Table 6 reports the results of the analysis using the models of equation (10), (11), (12), and

Table 6: Out-of-sample R^2. The results from the regression models in equation (10), (11), (12), and (14), respectively. The estimations are based on an expanding window using all past observations up to $t-1$ when making predictions about period t. The last two columns evaluates the out-of-sample R^2 over the subsample of days where the VIX ETP demand is negative and positive, respectively.

	R^2_{OOS} (%)		
Model	Full sample	$D^{VIXETP} < 0$	$D^{VIXETP} > 0$
Baseline	4.00	1.22	5.88
Asymmetric impact	5.24	1.20	7.96
Non-linear impact	4.91	-0.27	8.42
Gamma exposure interaction	4.54	-4.15	10.43

(14), respectively. The achieved levels of R-squared are remarkably high starting at 4.00% for the baseline model which is our most simple model. For comparison, Welch and Goyal (2008) find that none of the classical variables used in the literature to predict stock market returns can beat the historical return average. Campbell and Thompson (2008) revise the conclusions slightly and find that the classical predictors can out-perform the historical average under certain imposed model constraints. At a monthly return horizon, they achieve R-squared levels that in some cases are positive but always below 1%. When the return horizon is increased to one year, the latter paper is able to achieve better predictive performance with R-squared levels of the same magnitude that we find. For models predicting market returns, the values of the out-of-sample R-squared reported in Table 6 are higher than those obtained for intraday returns by Gao et al. (2018); Baltussen et al. (2021) but below the level of 6.57% found for overnight returns by Bondarenko and Muravyev (2022). We note that these studies forecast returns measured over 30 minutes or longer. It is well-established that in general, it is easier to achieve good performance in return prediction for longer horizons. In light of this, we believe that the strong performance of the VIX ETP demand in predicting SPX futures returns over the short 10 minutes window is striking.

Across the models listed in Table 6, the asymmetric model provides the best in-sample and out-of-sample fit to end-of-day returns. As the coefficient on $D_t^{VIXETP-}$ in Panel A of Table 5 is not significantly different from zero for any of the considered confidence levels, and since the hedging channel suggests that the strongest impact on SPX futures returns occurs when the

VIX ETP demand is postive, the last two columns of Table 6 shows the out-of-sample R-squared using only sample dates where the VIX ETP demand is negative and positive, respectively. The out-of-sample performance is much better for days with a positive VIX ETP demand. For instance take the asymmetric model with an out-of-sample R-squared of 7.96% relative to the 5.24% for the full sample. This again indicates that when dealers are hedging a short position the predictable power of our measure of VIX futures hedging activities is stronger. Overall, the results support an asymmetric relation.

4.4 Trading strategies based on the VIX ETP demand

We next examine if the end-of-day SPX futures return predictability coming from the VIX ETP rebalancing demand can be exploited through trading strategies. Based on the above results, we construct four trading strategies: Two that use only the VIX ETP rebalancing demand as a signal, and two that also incorporate the aggregate gamma exposure. Both the VIX ETP demand and the aggreagte gamma exposure are measured at 16:00.

The first strategy labeled $s(D)$, takes a short SPX futures position over the rebalancing window of 16:05-16:15 when $D_t^{VIX\,ETP}$ is positive and a long position when $D_t^{VIX\,ETP}$ is negative. The resulting return is

$$s(D) = \begin{cases} r^{ES}_{t,16:05-16:15} & \text{if } D_t^{VIX\,ETP} < 0, \\ -r^{ES}_{t,16:05-16:15} & \text{else.} \end{cases} \tag{16}$$

The differences in how market makers trade SPX futures to set up the hedge of a long and short VIX futures position, respectively, motivates the second strategy, $s(D^+)$. Since dealers should sell SPX futures to hedge a short VIX futures position but we are not certain how they trade SPX futures to hedge a long position, this strategy takes a short SPX futures position when $D_t^{VIX\,ETP}$ is positive and does not trade when it is negative. In this way we only trade on the days where we have the strongest belief about how dealers are trading SPX futures. Hence, the day t return of the strategy is

$$s(D^{+}) = \begin{cases} 0 & \text{if } D_t^{VIX\,ETP} < 0, \\ -r^{ES}_{t,16:05-16:15} & \text{else.} \end{cases} \tag{17}$$

On days of a positive net gamma position, option market makers act as contrarians as they rebalance by trading SPX futures in the opposite direction of the observed market movements. This means that they may cancel any SPX futures price impact generated by the activities of the VIX futures market makers. This would limit the predictability of the VIX ETP demand for end-of-day SPX futures returns. Conversely, the momentum trading by option market makers with a negative gamma exposure would strengthen the predictability. To capture this effect, the third strategy, $s(D,NGP,0)$, only trades on day t if NGP_t is negative and takes a long position if $D_t^{VIX\,ETP}$ is negative and a short position if $D_t^{VIX\,ETP}$ is positive. This yields a return of

$$s(D,NGP,0) = \begin{cases} r^{ES}_{t,16:05-16:15} & \text{if } D_t^{VIX\,ETP} < 0 \text{ and } NGP_t < 0, \\ -r^{ES}_{t,16:05-16:15} & \text{if } D_t^{VIX\,ETP} > 0 \text{ and } NGP_t < 0, \\ 0 & \text{else.} \end{cases} \tag{18}$$

The fourth strategy, $s(D,NGP,long)$, does almost the same but instead of not trading for days with positive NGP, it takes a long position on those days. This results in a return given by

$$s(D,NGP,long) = \begin{cases} r^{ES}_{t,16:05-16:15} & \text{if } D_t^{VIX\,ETP} < 0 \text{ and } NGP_t < 0, \\ -r^{ES}_{t,16:05-16:15} & \text{if } D_t^{VIX\,ETP} > 0 \text{ and } NGP_t < 0, \\ r^{ES}_{t,16:05-16:15} & \text{else.} \end{cases} \tag{19}$$

For comparison of the performance of the trading strategies, we use two benchmarks: *Always long*, which is long SPX futures over the 10-minute rebalancing window each day, and a pure buy-and-hold strategy in SPX futures, *Buy and hold*.

Measures of the performance of the trading strategies are shown in Panel A of Table 7. The returns on the three strategies $s(D)$, $s(D,NGP,0)$, and $s(D,NGP,long)$ have average returns

Table 7: Performance of trading strategies. The VIX ETP demand is measured at 16:00 and used as a signal for investing over 16:05-16:15. The strategy $s(D)$ takes a position in SPX futures which is long when $D^{VIX\,ETP} < 0$ and short when $D^{VIX\,ETP} > 0$. $s(D^{+})$ takes a short position in SPX futures over the rebalancing window, 16:05-16:15, when $D^{VIX\,ETP} > 0$ and when $NGP > 0$ nothing is done. $s(D, NGP, 0)$ does the same as $s(D)$ but only if $NGP < 0$. When $NGP > 0$, nothing is done. The strategy, $s(D, NGP, long)$, is similar to $s(D, NGP, 0)$ but instead of not trading when $NGP > 0$, a long SPX futures position is taken. *Always long* involves a long position over the rebalancing window while *Buy and hold* maintains a long SPX futures position over the entire sample period. Panel A ignores transaction costs while Panel B includes transaction costs corresponding to one tick. The mean and standard deviation of returns are annualized (assuming 252 trading days per year) and in percentages. t-statistics are based on the Newey-West estimator.

Strategy	Mean	Std. dev.	t-statistic	Sharpe ratio	Skewness	Kurtosis
Panel A: Without transaction costs						
$s(D)$	1.847	1.428	3.517	1.294	0.317	20.183
$s(D^{+})$	0.614	1.104	1.596	0.556	1.351	37.816
$s(D, NGP, 0)$	1.295	1.307	2.674	0.991	0.569	28.219
$s(D, NGP, long)$	2.004	1.427	3.803	1.405	0.380	20.192
Always long	0.619	1.432	1.149	0.432	-0.860	20.177
Buy and hold	12.780	16.317	2.131	0.783	-1.136	21.668
Panel B: With transaction costs						
$s(D)$	-0.967	1.429	-1.827	-0.677	0.341	20.088
$s(D^{+})$	-0.826	1.104	-2.132	-0.748	1.150	37.483
$s(D, NGP, 0)$	-0.203	1.306	-0.422	-0.156	0.413	28.192
$s(D, NGP, long)$	-0.810	1.429	-1.519	-0.567	0.404	20.061
Always long	-2.195	1.434	-4.025	-1.530	-0.830	19.968
Buy and hold	12.780	16.317	2.131	0.783	-1.136	21.668

that are strongly significant and positive. Compared with the benchmark strategies, all three display improved risk adjusted returns with a Sharpe ratio which is close to or above one. On the other hand, $s(D^{+})$ does not produce an average return significantly different from zero and has a Sharpe ratio of 0.56. In addition, we also highlight that all the strategies formed from the VIX ETP demand signal yield positively skewed returns in contrast to the two strategies based on long positions in the SPX futures. Earlier studies have shown how investors are willing to price in skewness and accept lower returns on assets with more positively skewed returns, see for instance Chang et al. (2013); Conrad et al. (2013).

The upper panel of Figure 7 also reveals the better performance of the three strategies, $s(D)$, $s(D, NGP, 0)$, and $s(D, NGP, long)$, compared to the strategy *Always long*. Among the three strategies, $s(D, NGP, 0)$ appears to perform the worst while the other two produce relatively

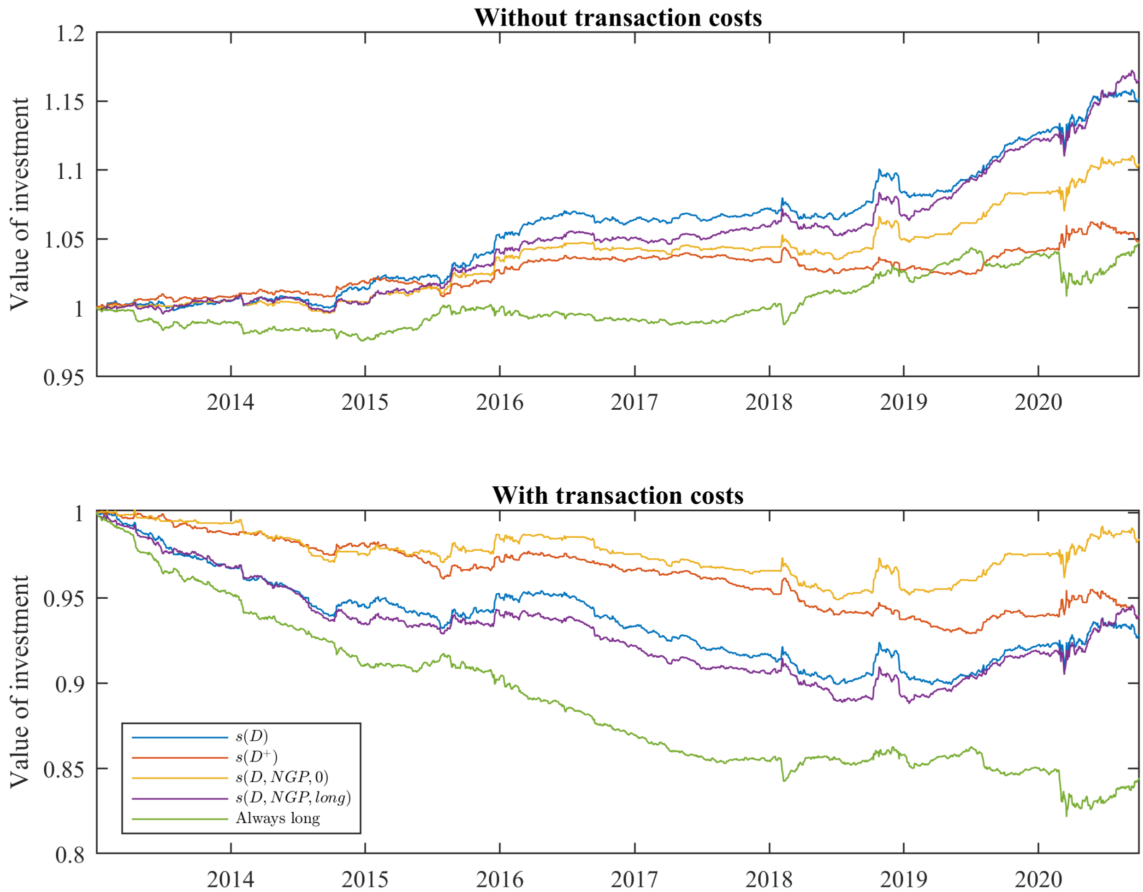

Figure 7: The value of a \$1 investment without and with transaction costs. The VIX ETP demand is measured at 16:00 and used as a signal for investing over 16:05-16:15. The upper panel ignores transaction costs while the lower panel includes transaction costs corresponding to one tick.

similar paths for the investment value over the sample period. Common to all four timing strategies is that on the day of the extreme volatility event on February 5, 2018, they correctly exploit the information in the VIX ETP demand producing a large positive return. On the same day, the SPX futures price experienced a large decrease. However, the profitability of the strategies is not only driven by this single event. At the beginning of the covid-19 pandemic, the four strategies appear to suffer less than the benchmark strategy *Always long*. During the first two years of the sample, we also see that losses accumulate for *Always long* while a positive return is realized for the timing strategies over the same period. After this period, $s(D^+)$ appears to perform worse relative to the other timing strategies and over the full period generates a cumulative return which is almost the same as that of *Always long*.

So far we have ignored transaction costs. Since the bid-ask spread provides a measure of the cost incurred from buying and selling a given asset, we use this to measure transaction costs. This is similar to the approach of e.g. Baltussen et al. (2021); Bondarenko and Muravyev (2022). For most of the time, the SPX futures bid-ask spread is one tick (0.25 index points) or \$12.5. Hence, we fix the bid-ask spread to one tick over the full sample meaning $spread_t^{ES} = 0.25$ for all t. The return on day t from the strategy, $s(D)$, is now given by

$$s(D) = \begin{cases} r^{ES}_{t,16:05-16:15} - \frac{spread_t^{ES}}{P^{ES}_{t,16:05}} & \text{if } D_t^{VIX\,ETP} < 0, \\ -r^{ES}_{t,16:05-16:15} - \frac{spread_t^{ES}}{P^{ES}_{t,16:05}} & \text{else.} \end{cases} \tag{20}$$

The same adjustment is applied to the returns for the other strategies listed above except for *Buy and hold* which only trades on the first and last day of the relevant period.

Panel B of Table 7 shows the performance of the strategies after adjusting returns for transaction costs. Likewise, the lower panel in Figure 7 shows the cumulative value of strategies with transaction costs. Both reveal that none of the strategies are profitable once transaction costs are present. The trading strategy, $s(D,NGP,0)$, does not trade on 46% of the days which partly explains why it is superior once transaction costs are included. However, the same argument does not apply to $s(D^+)$ which only trade on 49% of the days. Hence, information on the net gamma position seems to add value to the strategy.

The above shows that transaction costs can easily consume all profits. This indicates the need for a more sophisticated approach for chosing when to trade. We do this by relying on the models in equation (10), (11), (12), and (14), respectively. Thus, we only trade SPX futures on a given day if the absolute price change over the rebalancing window obtained from the models is above transaction costs. This means that trading only takes place when the signal from the VIX ETP demand is sufficiently strong. Furthermore, the direction in which to trade SPX futures is determined by the VIX ETP demand through the sign of the estimated return: Once it is positive, we take a long position while a negative estimated return indicates that we

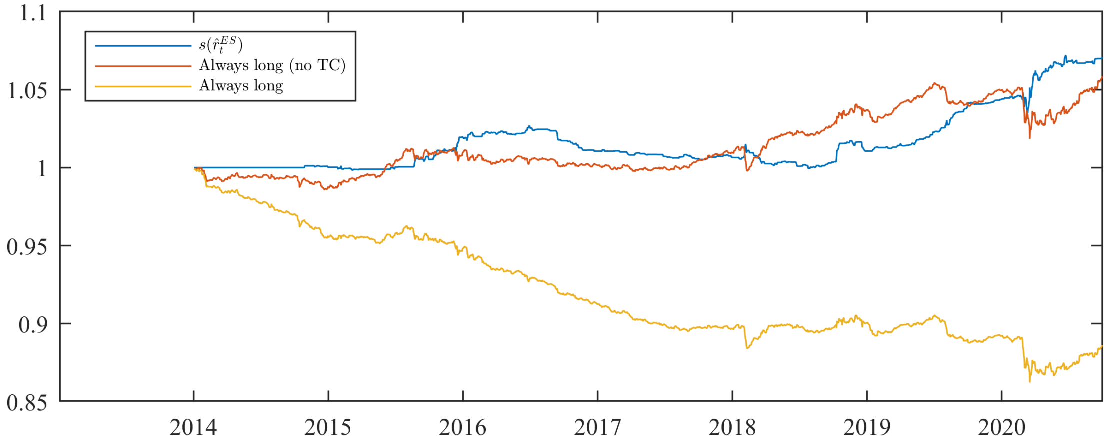

Figure 8: The value of a \$1 investment including transaction costs. The VIX ETP demand is measured at 16:00, and the investment is over 16:05-16:15. The strategy relies on the trading rule in equation (21) with predicted returns from the model in equation (10). The model is estimated using an expanding window. Based on the estimated model, fitted values, $\hat{r}^{ES}_{t,16:05-16:15}$, are obtained for each t. Trading only takes place if the estimated absolute price change over the rebalancing window is above the tick size (0.25 index points). If, in addition to this condition, the estimated return is positive (negative), a long (short) SPX futures position is held while reducing the realized return by one tick. When the condition for trading is not satisfied, returns are zero. For the first model estimation, one year of data is used such that strategy evaluation begins on January 2, 2014. The statistics are computed from January 2, 2014 and over the remainder of the sample period.

should take a short position. The return from the strategy is then given by

$$s(\hat{r}_t^{ES}) = \begin{cases} r^{ES}_{t,16:05-16:15} - \frac{spread^{ES}_t}{P^{ES}_{t,16:05}} & \text{if } \left|\widehat{\Delta P}^{ES}_{t,16:05-16:15}\right| - spread^{ES}_t > 0 \text{ and } \hat{r}^{ES}_{t,16:05-16:15} > 0, \\ -r^{ES}_{t,16:05-16:15} - \frac{spread^{ES}_t}{P^{ES}_{t,16:05}} & \text{if } \left|\widehat{\Delta P}^{ES}_{t,16:05-16:15}\right| - spread^{ES}_t > 0 \text{ and } \hat{r}^{ES}_{t,16:05-16:15} < 0, \\ 0 & \text{else,} \end{cases} \tag{21}$$

where $\hat{r}_t^{ES}$ is the estimated return from one of the models. When evaluating the strategy, we estimate the models using an expanding window. We use one year of data for the first model estimation such that the strategies are implemented beginning from January 2, 2014. Using the baseline regression model in equation (10), we show the cumulative value of a \$1 investment in Figure 8. The path indicates that the modified strategy is profitable even after transaction costs. Table 8 also reveals that a significantly positive return of 1.03% annually can be earned from the strategy based on the baseline model in equation (10). With a Sharpe ratio of 0.91, it appears that this strategy actually outperforms the benchmark strategy which is always long

Table 8: Performance of trading strategies including transaction costs. The VIX ETP demand is measured at 16:00, and the investment is over 16:05-16:15. The strategies rely on the trading rule in equation (21) with predicted returns from the models in equation (10), (11), (12), and (14), respectively. All the models are estimated using an expanding window. Based on the estimated model, predicted values, $\hat{r}^{ES}_{t,16:05-16:15}$, are obtained for each t. Trading only takes place if the estimated absolute price change over the rebalancing window is above the tick size (0.25 index points). If, in addition to this condition, the estimated return is positive (negative), a long (short) SPX futures position is held. When the condition for trading is not satisfied, returns are zero. For the first model estimation, one year of data is used such that strategy evaluation begins on January 2, 2014. The statistics are computed from January 2, 2014 and over the remainder of the sample period. The mean and std.dev. of returns are annualized (assuming 252 trading days per year) and in percentages. t-statistics are based on the Newey-West estimator.

Strategy	Mean	Std. dev.	t-statistic	Sharpe ratio	Skewness	Kurtosis
Baseline	1.028	1.132	2.394	0.908	1.092	50.433
Asymmetric impact	0.872	1.171	2.111	0.745	0.343	41.081
Non-linear impact	0.752	0.990	1.830	0.760	1.023	77.428
Gamma exposure interaction	0.467	1.081	1.124	0.432	0.971	61.057
Always long (no TC)	0.863	1.491	1.448	0.579	-0.880	19.617
Always long	-1.797	1.492	-2.992	-1.204	-0.863	19.481
Buy and hold	10.689	16.959	1.592	0.630	-1.128	21.157

over the rebalancing window even if the latter is not subject to transaction costs. This infeasible benchmark strategy generates an annualized return of 0.86% and has a Sharpe ratio of 0.58.

The cumulative return of the strategies appear rather modest given the relatively long investment horizon. However, we should keep in mind that the strategy only ties up capital over a 10 minutes interval of the day. Outside this short window, the capital is free to pursue other investments.

4.5 Reversal

Given that VIX futures trades by VIX ETPs correspond to a mechanically driven hedging demand, we would associate the VIX futures demand of VIX ETPs with uninformed trading. As mentioned in Section 3.3, this view has recieved support by existing studies of the VIX futures market. If the VIX ETP demand is truely uninformed, we would expect that the corresponding price impact in the SPX futures market is only transitory, and we therefore examine the relation between the SPX futures returns and VIX ETP demand after the rebalancing has ended. The window over which we look for reversal begins at the point where rebalancing of VIX ETPs is assumed to have stopped, namely at 16:15, and ends at 10:00 the next trading day. Hence, for analyzing the reversal of SPX futures returns, we consider the following regression model

$$r^{ES}_{t,16:15-t+1,10:00} = \alpha + \beta D^{VIX\,ETP}_{t} + u_t, \tag{22}$$

where the rebalancing variable, $D^{VIX\,ETP}_{t}$, is now measured from 16:15 on day $t-1$ to 16:15 on day t such that it also contains the VIX ETP rebalancing needs accumulated from 16:00 to 16:15. A transitory price impact from rebalancing would be consistent with a positive value of β as this corresponds to a reversal of the initial price impact.

Table 9 shows the results from the regression in (22). In the full model in column (7), the coefficient on the VIX ETP rebalancing variable has a positive sign but is insignificant. This makes it less clear whether the price impact found in Table 4 is the result of transitory price pressures from VIX futures dealers.

Again, we consider the variations of the baseline regression model by allowing for asymmetric and non-linear impacts and the effect of an interaction with simultaneous option rebalancing. The results are shown in Table 10. In Panel A, the coefficient on the positive part of VIX ETP demand is positive and significant in the full model of column (7). The change of sign of the estimate relative to that observed in Table 5 indicates that a reversal takes place when VIX ETPs must rebalance by buying VIX futures. However, the coefficient is not significant for any of the other combinations of the control variables. For the case of a non-linear impact, the results of Panel B are consistent with a stronger tendency for return reversals when VIX ETP demand is large in absolute value. This relation is significant at the 1% significance level across all the set of control variables, and the size of the coefficient on the squared VIX ETP demand is also stable. Finally, the positive coefficient estimates for the VIX ETP demand and net gamma position interaction terms in Panel C are indicative of a reversal yet the estimates remain insignificant. Overall, we see that allowing for a more flexible link between the SPX

Table 9: SPX futures return over the reversal window. The table reports the regression results for the model in equation (22). D_t^{VIXETP} is the VIX ETP rebalancing demand measured at 16:15, and $r_{t,09:30-16:05}^{ES}$ and $r_{t,09:30-16:05}^{\overline{VX}}$ are the returns on the SPX futures contract and the VIX futures short-term index, respectively, up to the beginning of the rebalancing window. $Vol_{t,09:30-16:05}^{ES}$ is the SPX futures volume up to the rebalancing window. VIX_t denotes the level of the VIX index, $RV_{t,16:05-16:15}^{ES}$ is the SPX futures realized volatility over the rebalancing window, and $sVol_{t,09:30-16:05}^{VX}$ is the VIX futures signed volume up to the beginning of the rebalancing window on day t. The variables have been standardized. Newey-West t-statistics are in parentheses. ***, **, * indicates 1%, 5% and 10% significance, respectively.

$r_{t,16:15-t+1,10:00}^{ES}$	(1)	(2)	(3)	(4)	(5)	(6)	(7)
D_t^{VIXETP}	-0.009	0.017	-0.008	-0.008	-0.019	-0.002	0.016
	(-0.220)	(0.422)	(-0.200)	(-0.197)	(-0.461)	(-0.060)	(0.400)
$r_{t,09:30-16:05}^{ES}$		-0.151					-0.153
		(-1.591)					(-1.619)
$r_{t,09:30-16:05}^{\overline{VX}}$		-0.149*					-0.201**
		(-1.701)					(-2.052)
$Vol_{t,09:30-16:05}^{ES}$			-0.017				0.021
			(-0.417)				(0.560)
VIX_t				-0.042			0.031
				(-0.398)			(0.292)
$sVol_{t,09:30-16:05}^{VX}$					0.023		0.080**
					(0.938)		(2.062)
$RV_{t,16:05-16:15}^{ES}$						-0.067	-0.105
						(-0.763)	(-1.608)
Adj. R^2 (%)	-0.05	0.97	-0.07	0.07	-0.05	0.31	1.54
No. of Obs.	1900	1900	1900	1900	1900	1900	1900

futures returns and our measure of the VIX futures hedging activities, there is some indication that hedging activities lead to a transitory price impact.

5 Conclusion

We show how VIX futures market makers can hedge their exposure by a delta-hedged SPX option position. Since the delta-hedging is typically implemented using SPX futures, the presence of the market maker's hedging transactions gives rise to the question of how these transactions influence the SPX futures market. We analyze this by computing the VIX futures demand by VIX ETPs over an extended period, and interpret this as a proxy for VIX futures market makers' hedging activities in SPX futures at the end of the trading day. We show that the VIX ETP demand impacts the SPX futures market in the direction consistent with how

Table 10: SPX futures return over the reversal window. Each column reports the results using different sets of control variables. The variables have been standardized. Newey-West t-statistics are in parentheses. ***, **, * indicates 1%, 5% and 10% significance, respectively.

$r^{ES}_{t,16:15-t+1,10:00}$	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Controls	None	$r^{ES}_{t,09:30-16:05}$ $r^{VX}_{t,09:30-16:05}$	$Vol^{ES}_{t,09:30-16:05}$	VIX_t	$sVol^{VX}_{t,09:30-16:05}$	$RV^{ES}_{t,16:05-16:15}$	All
Panel A: Asymmetric impact							
$D^{VIXETP-}_t$	-0.052	-0.037	-0.057*	-0.060	-0.056*	-0.067*	-0.058*
	(-1.613)	(-1.386)	(-1.659)	(-1.468)	(-1.731)	(-1.661)	(-1.709)
$D^{VIXETP+}_t$	0.035	0.054	0.042	0.043	0.028	0.059	0.072*
	(1.070)	(1.427)	(1.303)	(1.259)	(0.811)	(1.575)	(1.841)
Adj. R^2 (%)	0.20	1.23	0.24	0.42	0.18	0.82	2.06
No. of Obs.	1900	1900	1900	1900	1900	1900	1900
Panel B: Non-linear impact							
D^{VIXETP}_t	-0.066*	-0.048	-0.066*	-0.067*	-0.077*	-0.066*	-0.057
	(-1.790)	(-1.358)	(-1.788)	(-1.802)	(-1.949)	(-1.853)	(-1.564)
$(D^{VIXETP}_t)^2 \times s_t$	0.088***	0.098***	0.090***	0.091***	0.088***	0.099***	0.111***
	(3.926)	(4.037)	(3.822)	(3.610)	(3.985)	(3.599)	(4.090)
Adj. R^2 (%)	0.36	1.49	0.36	0.51	0.36	0.83	2.20
No. of Obs.	1900	1900	1900	1900	1900	1900	1900
Panel C: Gamma exposure interaction							
$D^{VIXETP}_t(1-NGP^-_t)$	0.014	0.035	0.016	0.017	0.011	0.024	0.038
	(0.320)	(0.767)	(0.365)	(0.391)	(0.230)	(0.558)	(0.802)
$D^{VIXETP}_t e^{-NGP^+_t}$	0.008	0.016	0.007	0.008	0.007	0.009	0.016
	(0.488)	(0.898)	(0.440)	(0.482)	(0.438)	(0.508)	(0.912)
Adj. R^2 (%)	-0.08	1.06	-0.09	0.06	-0.12	0.33	1.63
No. of Obs.	1896	1896	1896	1896	1896	1896	1896

VIX futures market makers should trade SPX futures to hedge. In specific, we find that the VIX ETP demand is a strong predictor of the end-of-day SPX futures return both in-sample and out-of-sample. Motivated by these results, we construct different trading strategies based on VIX ETP demand and show that historically it has been possible to monetize the hedging impact.

The hedging transactions could benefit the SPX futures market by increasing the flow of information from the VIX futures market to the SPX futures market, while the mechanical nature of hedging also raises the concern that it could destabilize the stock market. We test for a possible reversal in price overnight and find some support for a reversal. This finding indicates that VIX futures hedging can move the SPX futures market via mechanisms unrelated to informed trading with potentially destabilizing impact in stressed market situations.

Acknowledgment

The research presented in this paper has been conducted with support from the Danish Council for Independent Research (Grant: DFF 0133-00151B). The authors wish to thank Zhi Da, Elisa Nicolato, Anders Merrild Posselt, Carsten Tanggaard, and seminar participants at Aarhus University for useful comments. The paper has been presented at the following conferences: 29th Finance Forum, and International Risk Management Conference 2022.

References

Alexander, C. and Korovilas, D. (2013). Volatility exchange-traded notes: Curse or cure? *Journal of Alternative Investments*, 16(2):52–70.

Augustin, P., Cheng, I.-H., and Van den Bergen, L. (2021). Volmageddon and the failure of short volatility products. *Financial Analysts Journal*, pages 1–17.

Avellaneda, M. and Lipkin, M. (2003). A market-induced mechanism for stock pinning. *Quantitative Finance*, 3(6):417–425.

Baltussen, G., Da, Z., Lammers, S., and Martens, M. (2021). Hedging demand and market intraday momentum. *Journal of Financial Economics*, 142(1):377–403.

Baltussen, G., van Bekkum, S., and Da, Z. (2019). Indexing and stock market serial dependence around the world. *Journal of Financial Economics*, 132(1):26–48.

Bangsgaard, C. D. and Kokholm, T. (2022). The lead-lag relation between VIX futures and SPX futures. Available at SSRN 4003464.

Bank for International Settlements (2018). BIS Quarterly Review, March 2018: International banking and financial market developments. Technical report, available at https://www.bis.org.

Barbon, A., Beckmeyer, H., Buraschi, A., and Moerke, M. (2022). Liquidity provision to leveraged ETFs and equity options rebalancing flows: Evidence from end-of-day stock prices. Available at SSRN 3925725.

Barbon, A. and Buraschi, A. (2021). Gamma fragility. Available at SSRN 3725454.

Ben-David, I., Franzoni, F., and Moussawi, R. (2018). Do ETFs increase volatility? *Journal of Finance*, 73(6):2471–2535.

Bhansali, V. and Harris, L. (2018). Everybody's doing it: Short volatility strategies and shadow financial insurers. *Financial Analysts Journal*, 74(2):12–23.

Bollen, N. P., O'Neill, M. J., and Whaley, R. E. (2017). Tail wags dog: Intraday price discovery in VIX markets. *Journal of Futures Markets*, 37(5):431–451.

Bondarenko, O. and Muravyev, D. (2022). Market return around the clock: A puzzle. Available at SSRN 3596245.

Brogaard, J., Carrion, A., Moyaert, T., Riordan, R., Shkilko, A., and Sokolov, K. (2018). High frequency trading and extreme price movements. *Journal of Financial Economics*, 128(2):253–265.

Brøgger, S. B. (2021). The market impact of predictable flows: Evidence from leveraged VIX products. *Journal of Banking & Finance*, page 106280.

Campbell, J. Y. and Thompson, S. B. (2008). Predicting excess stock returns out of sample: Can anything beat the historical average? *Review of Financial Studies*, 21(4):1509–1531.

Chang, B. Y., Christoffersen, P., and Jacobs, K. (2013). Market skewness risk and the cross section of stock returns. *Journal of Financial Economics*, 107(1):46–68.

Chang, J. (2017). Monthly Market Review, November 2017: A "vixing" puzzle. pages 1–3. Rockefeller Asset Management.

Chen, Y.-L. and Tsai, W.-C. (2017). Determinants of price discovery in the VIX futures market. *Journal of Empirical Finance*, 43:59–73.

Cheng, M. and Madhavan, A. (2010). The dynamics of leveraged and inverse exchange-traded funds. *Journal of Investment Management*, 16(4):43–62.

Conrad, J., Dittmar, R. F., and Ghysels, E. (2013). Ex ante skewness and expected stock returns. *The Journal of Finance*, 68(1):85–124.

Fernandez-Perez, A., Frijns, B., Tourani-Rad, A., and Webb, R. I. (2019). Does increased hedging lead to decreased price efficiency? The case of VIX ETPs and VIX futures. *Financial Review*, 54(3):477–500.

Frijns, B., Tourani-Rad, A., and Webb, R. I. (2016). On the intraday relation between the VIX and its futures. *Journal of Futures Markets*, 36(9):870–886.

Gao, L., Han, Y., Li, S. Z., and Zhou, G. (2018). Market intraday momentum. *Journal of Financial Economics*, 129(2):394–414.

Garleanu, N., Pedersen, L. H., and Poteshman, A. M. (2009). Demand-based option pricing. *Review of Financial Studies*, 22(10):4259–4299.

Golez, B. and Jackwerth, J. C. (2012). Pinning in the S&P 500 futures. *Journal of Financial Economics*, 106(3):566–585.

Goyenko, R. and Zhang, C. (2019). Option returns: Closing prices are not what you pay. Unpublished working paper McGill University.

Hu, J. (2014). Does option trading convey stock price information? *Journal of Financial Economics*, 111(3):625–645.

Kirilenko, A., Kyle, A. S., Samadi, M., and Tuzun, T. (2017). The flash crash: High-frequency trading in an electronic market. *The Journal of Finance*, 72(3):967–998.

Ni, S. X., Pearson, N. D., and Poteshman, A. M. (2005). Stock price clustering on option expiration dates. *Journal of Financial Economics*, 78(1):49–87.

O'Neill, M. and Whaley, R. E. (2021). Effects of nondiscretionary trading on futures prices. Available at SSRN 3880082.

Shu, J. and Zhang, J. E. (2012). Causality in the VIX futures market. *Journal of Futures Markets*, 32(1):24–46.

Shum, P., Hejazi, W., Haryanto, E., and Rodier, A. (2016). Intraday share price volatility and leveraged ETF rebalancing. *Review of Finance*, 20(6):2379–2409.

Sornette, D., Ulmann, F., and Wehrli, A. (2022). On the directional destabilizing feedback effects of option hedging. *Swiss Finance Institute Research Paper No. 22-34*.

S&P Dow Jones Indices (2021). S&P VIX Futures Indices Methodology. Retrieved from us.spindices.com/indices/strategy/sp-500-vix-short-term-index-mcap.

Todorov, K. (2021). Passive funds affect prices: Evidence from the most ETF-dominated asset classes. Available at SSRN 3504016.

Welch, I. and Goyal, A. (2008). A comprehensive look at the empirical performance of equity premium prediction. *Review of Financial Studies*, 21(4):1455–1508.

Whaley, R. E. (2009). Understanding the VIX. *Journal of Portfolio Management*, 35(3):98–105.