The Impact of Net Buying Pressure on VIX Option Prices

Yi-Wei Chuang, Wei-Che Tsai, and Ming-Hung Wu*

ABSTRACT

This paper analyzes the impact of intraday trading pressures on option prices in the VIX options market. Our results show that there is a temporal relationship between net buying pressure and changes in implied volatility of VIX options. Moreover, an increase in net buying pressure of VIX call options lowers the next-day delta-hedged option returns. Using several measures proxying for the magnitude of limits to arbitrage, our empirical results document that the levels of the implied volatility curve of VIX options rise when there are more severe limits to arbitrage. When constructing a trading strategy in the VIX futures market by utilizing the net buying pressure of VIX options, it generates an average annualized adjusted return of 10.09%. Overall, the evidence of intraday trading pressure on VIX options likely provides support for the limits to arbitrage hypothesis rather than the information hypothesis.

Keywords: Limits of arbitrage, Net buying pressure, VIX options, Implied volatility of volatility.

JEL Classification: G13.

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This paper analyzes the impact of intraday trading activity on option prices in the VIX options market. Our results show that there is a temporal relationship between net buying pressure and changes in implied volatility of VIX options. Moreover, an increase in net buying pressures of VIX options lowers the next-day delta-hedged option returns. Using several measures proxying for the magnitude of limits to arbitrage, our empirical results document that the levels of the implied volatility curve of VIX options rise when there are more severe limits to arbitrage. When constructing a trading strategy in the VIX futures market by utilizing net buying pressure of VIX options, it generates an average annualized adjusted return of 10.09%. Overall, the evidence of intraday trading pressure on VIX options likely provides support for the limits to arbitrage hypothesis rather than the information hypothesis.

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1. INTRODUCTION

Unlike in a perfectly efficient market, trading activity usually impacts market prices in ‘real world’ financial markets. For example, market makers may face inventory control problems during periods of large order imbalances. If the trading amount of buy orders is slightly greater than that of sell orders and exceeds the quantities that market makers can provide at that time, then the large order imbalance will force them to respond by raising quoted prices (see e.g. Stoll (1978), Ho and Stoll (1983), Spiegel and Subrahmanyam (1995), and Chordia, Roll, and Subrahmanyam (2002)). Although higher prices caused by temporary order imbalance may attract arbitrageurs to step in and help asset prices revert to fundamental values, mispricing may still persist due to limits to arbitrage (see for example, Shleifer and Vishny (1997), Gromb and Vayanos (2002), and Brunnermeier and Pedersen (2009)).

Evidence of trading pressure has also been documented in the equity derivatives markets. Gârleanu, Pedersen, and Poteshman (2009) provide a theoretical model of trading demand pressure on option pricing, whereas Muravyev (2016) shows that the price impact of daily order imbalances in equity option markets attributable to inventory risk is also quite large. Bollen and Whaley (2004) also find that net buying pressure of equity options, constructed as the number of buyer-motivated contracts traded each day minus the number of seller-motivated contracts, contributes to daily changes in the level and slope of implied volatility.

Order imbalance may reflect informed trading in addition to having an inventory risk impact. As Stoll (2000) and Schlag and Stoll (2005) suggest, informed trading does have a permanent influence on market prices. Several studies provide support for the existence of informed trading in the equity options markets, such as Easley, O’Hara and Srinivas (1998), Pan and Poteshman (2006), Cremers and

Weinbaum (2010), Roll, Schwartz and Subrahmanyam (2010), Xing, Zhang, and Zhao (2010), Johnson and So (2012), Conrad, Dittmar, and Ghysels (2013), An, Ang, Bali and Cakici (2014), Hu (2014), and Chesney, Crameri and Mancini (2015).

With regard to volatility asset classes, this study first aims to provide a comprehensively empirical analysis on the impact of intraday trading activity of VIX options on their market prices.[1] Our findings clearly demonstrate that there is a temporal relationship between net buying pressure of VIX options and changes in implied volatility of VIX options. In other words, the increased net buying pressure of VIX options have a slight impact on its corresponding market prices, regardless of calls or puts. In addition, we find that higher net buying pressure of VIX calls predicts lower the next-day delta-hedged option returns, representing that trading pressure affects market maker's pricing for VIX options, resulting in lower delta-hedged returns.

Our paper further examines the relationship between the level of the implied volatility curve and proxy variables for measures of limits to arbitrage. These proxy variables include measures of implementation risk (bid–ask spread and trading volume), noise-trader risk (investor attention and sentiment), and funding liquidity (Libor-Tbill and Libor-Repo spreads). The result shows that the level of the implied volatility curve in the VIX options market rises when there are serious limits to arbitrage.

As motivated by Hu (2014) that options liquidity providers' hedging positions

[1] Chung, Tsai, Wang, and Weng (2011) utilize daily market prices of VIX options to provide support for the informational role of VIX options regarding returns, volatility, and density predictions in the S&P 500 index. Wang (2013) finds that the daily trading volume of VIX call options is informative regarding future realized volatility. Tsai, Chiu, and Wang (2015) show that volume imbalances convey no significant predictive information, while quote changes in VIX options can significantly predict changes in the index; this predictive power is especially more pronounced for VIX calls around periods of monetary policy announcements.

in the underlying asset changes the underlying asset's price, we also create a trading strategy in the VIX futures market by using the net buying pressure of VIX options. The trading strategy in the VIX futures market generates an average annualized risk-adjusted return of 10.09%, providing evidence of option trading pressure transmission to its futures market via hedging activity.

This study focuses on high-frequency intraday level to gain a better understanding of the process of intraday price formation in an actively exchange-traded volatility asset. Overall, our results of the relationship between trading activity and market prices generally provide support for the effects of limits-to-arbitrage rather than informed trading. This also complements the knowledge of volatility assets and will help attribute the causal effect of limits-to-arbitrage to the volatility asset class.

The remainder of this article is organized as follows. Section 2 offers the literature review and describes the hypothesis development. Section 3 presents the data used for analysis and the empirical methodology herein. Section 4 shows empirical results, and Section 5 makes the concluding remarks.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

In theory, as noted in Dybvig and Ross (1992) and Shleifer and Vishny (1997), arbitrage requires no capital and is risk-free. However, in the real-world financial markets, arbitraging transactions almost always need capital and can entail various degrees of risk.[2] Furthermore, they also revert asset prices back to their fundamental value and hence eliminating the misplaced price.

[2] In fact, as Figlewski (1989) argue, arbitrageurs cannot hedge their positions perfectly even if there are profitable arbitrage opportunities in the financial markets, because of the impossibility of trading continuously, transaction costs, price jumps, and so on.

Capital constraint is one important reason explaining the presence of limits to arbitrage since the existing literature on limits to arbitrage has widely recognized the importance in the financial markets. If arbitrageurs do not have access to additional capital when securities prices diverge, then they may be forced to prematurely liquidate the positions and be exposed to a risk of losses, see for example, Shleifer and Summers (1990), Shleifer and Vishny (1997), and Liu and Longstaff (2004). On the other hand, the noise trader theory of De Long, Shleifer and Summers (1990) suggests that the presence of noise traders would prevent arbitrageurs from converging security prices to their fundamental values. In addition, as stocks without close substitutes, arbitrages are limited and mispricing is likely to be more frequent, see e.g, Wurgler and Zhuravskaya (2002).

A few studies present evidences of impacts of limit to arbitrage on derivatives prices. For example, Bollen and Whaley (2004) find that order imbalance in the option markets both affects the changes in the level and slope of implied volatility, suggesting that liquidity providers require a premium to compensate for buying pressure. Gârleanu et al. (2009) also provide a theoretical model of demand pressure effects in the options market and suggest that the price effects may be due to market makers being capital-constrained and unable to perfectly hedge their inventories; thus, option demand impacts prices. Liquidity providers may face expensive hedging costs for insurance when they are funding-constrained in their ability to provide liquidity, see e.g., Brunnermeier and Pedersen (2009).[3] Cao and Han (2013) present that market makers require a higher premium for options on high idiosyncratic volatility stocks when there are high arbitrage costs. Recently, Muravyev (2016)

[3] Gromb and Vayanos (2002) suggest that leverage constraints affect the ability of arbitrageurs to eliminate mispricing. Their model indicates that arbitrage activity benefits all investors, because arbitrageurs supply liquidity to the market.

documents that price impact of daily order imbalances in the options markets attributable to inventory risk is large.

In contrast to the limits to arbitrage hypothesis, net buying pressure may capture the presence of informed traders in the derivative markets. Easley et al. (1998) show that options is the instrument of choice for informed traders, because option volumes contain information about future stock prices. Kang and Park (2008) argue that option demand changes the expectations of investors regarding the future price movements of the underlying asset, leading to changes in option prices. They find that the net buying pressure of call and put options are opposite direction to influences on implied volatility, providing support for the notion of forward-looking information contained in the options markets. This therefore leads to the information hypothesis, which aims to provide a better understanding of the informational role of net buying pressure in the VIX options market, an issue yet to be documented within the related literature.

We evaluate the two hypotheses through the relationships between changes in implied volatility and net buying imbalance in the VIX options market: (1) The limit to arbitrage hypothesis and (2) the information hypothesis. Following empirical methodology of Bollen and Whaley (2004) and Kang and Park (2008), our regression models include the lagged change in implied volatility as an independent variable and study the relationship between changes in implied volatility and net buying imbalance. Bollen and Whaley (2004) suggest that limit to arbitrage hypothesis assumes that the upward sloping supply curve is possible due to the limits to arbitrage. As market makers are risk-averse, they will not stand ready to sell an unlimited number of contracts in an option series, even if there are profitable arbitrage opportunities in the market. Because market makers may face inventory control problems during periods of large order imbalances, and then there is a possibility that mark-to-market losses may force liquidation of their positions before convergence. If each option contract has an upward sloping supply curve, each implied volatilities is determined to depend on the demand for each option contract. Thus, under the limits-to-arbitrage hypothesis, trading demand for options pushes up implied volatility because liquidity providers require a higher premium due to the presence of limits to arbitrage. In this case, the increases in VIX option prices induced by the increases in net buying pressure would be temporary. They revert to the fundamental values as liquidity providers rebalance their inventory positions. On the other hand, the information hypothesis predicts no serial correlation in implied volatility changes because trading activities in the VIX options market quickly reflect all information in option prices. The relationship between net buying pressure and changes in implied volatility would be permanent if net buying pressure contains information.

It would be worth to further explore option market participants' supply and demand for different option series. Option prices change only when new information hits the market. Bollen and Whaley (2004) assume that option traders are volatility traders and focus only on volatility shocks. If a volatility shock occurs and an order imbalance signals the shock to investors, then the order imbalance will change the expectations of investors concerning future volatility; thus, the implied volatility will change. In other words, the trading activity of investors provides information to the market maker, who continually learns about the underlying asset dynamics and updates prices as a result. Therefore, we may observe a positive relationship between net buying pressure and implied volatility. Thus, under the limit to arbitrage hypothesis, option prices are expected to be affected by its trading pressure. The implied volatilities of different option series need not move together as they are primarily affected by option series' own demand. In other words, net buying pressure on a particular option contract will have no impact on other option series. For example, the net buying pressure of the ATM (at-the-money) options does not necessarily affect the ITM (in-the-money) or OTM (out-of-the-money) option prices. In contrast, under the information hypothesis, the net buying pressure for the ATM options would generate impacts on changes in other option contracts, since ATM options usually have the most informative about future volatility. In this case, market prices of all option series would move together in concert with each other.

3. EMPIRICAL METHODOLOGY AND DATA DESCRIPTION

3.1 Data and sample statistics

We obtain the VIX options dataset from the Chicago Board Options Exchange (CBOE). This dataset includes high-frequency intraday VIX futures and options transaction data for 566 trading days over the period from January 2008 to March 2010. We apply the following filters to the options data: (i) we only use data of regular trading hours from 8:30 a.m. to 3:15 p.m.; (ii) the contract has positive and non-missing volume data; (iii) we eliminate non-positive bid quotes or bid prices that are greater than or equal to the ask prices;[4] (iv) we eliminate data errors, such as trades with zero prices or zero strike prices; (v) implied volatility of volatility (IVOV) is between 10% and 150%; and (vi) option matures within 8-90 days.[5] Moreover, the VIX futures returns are defined as the first difference of the natural log of the VIX futures in each trading interval. The VIX futures dollar trading

[4] We filter out (i)-(iii), because the trade direction classification is less reliable for those trades and avoids microstructure-related bias.

[5] The maturity filter is similar to Park (2015). The results are the same for containing long-term options, although they are not reported in this study.

volumes are calculated as each trading volume times trading price.

The trades' executed directions are classified according to the Lee and Ready (1991) algorithm.[6] All transactions can be categorized based upon this approach, with the exception of any occurrence of a first trade executed at the midpoint. Such exceptions are defined as non-classified transactions.

To calculate VIX option implied volatility and delta, we use the VIX option pricing model (Whaley, 1993) presented as:

$$c = e^{-rT}\left[F_0 N(d_1) - KN(d_2)\right], \text{ and } p = e^{-rT}\left[KN(-d_2) - F_0 N(-d_1)\right], \tag{1}$$

$$d_1 = \frac{\ln(F_0/K) + 0.5\sigma^2 T}{\sigma\sqrt{T}}, \text{ and } d_2 = \frac{(F_0/K) - 0.5\sigma^2 T}{\sigma\sqrt{T}}, \tag{2}$$

where c and p denote the respective price of VIX call and put options; F_0 is the VIX futures price; r is the continuously compounded zero-coupon interest rate that proxies for the risk-free rate; K is the strike price; $N(\cdot)$ is the standard normal cumulative distribution function; and T is the time to maturity.[7]

We classify VIX options into three different moneyness groups by delta and then use an average implied volatility of each group to calculate the change in implied volatility.[8] The VIX option delta is as follows:

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[6] Following the quote rule, we classify a VIX option trade as buyer-initiated (seller-initiated) if the transaction price is above (below) the most recent mid-quote price. When the trade price is the same as the most recent mid-quote price or when no valid quote exists, the quote rule fails to classify a trade. In such cases, we apply the tick rule: If the trade price is above (below) the previous trade price, then it is classified as buyer-initiated (seller-initiated). This procedure of applying the tick rule after the quote rule first appears in Lee and Ready (1991).

[7] Bollen, O'Neill and Whaley (2017) find that the price relation between the VIX futures and VIX options are linked by put-call parity.

[8] The traditional measure of moneyness for options based on the underlying price to strike price ratio fails to clarify the likelihood that the option will be in-the-money upon expiration, which also depends on the underlying volatility and time to maturity. Following Bollen and Whaley (2004), we use the options' delta to account for these effects, because delta is sensitive to underlying volatility and time to maturity.

$$Delta_{call} = e^{-rT} N(d_1) \text{ and } Delta_{put} = -e^{-rT} N(-d_1). \tag{3}$$

We calculate the VIX options' delta for each option trade using the valuation methodologies and parameter assumptions described above. Based on their deltas, VIX options are then arranged into three moneyness groups. Table 1 presents the boundary of each moneyness group used herein and lists the moneyness, the corresponding delta ranges, and the category numbers of options in our sample. To avoid potential distortions caused by price discreteness, VIX options with absolute deltas below 0.05 and above 0.95 are excluded.

Table 1 reports the buyer-initiated (seller-initiated) volume and proportion for each group. VIX calls initiated 58.8% of the total option trades, while VIX puts initiated 41.2% of the total option trades. Comparing across moneyness categories, the trading volumes for VIX calls are the most active for OTM options (category 3). Similar to VIX puts, OTM put options (category 1) are also the most active category of puts traded. Comparing initiated types, buyer-initiated trades (52.58%) occur more than seller-initiated trades (46.58%).

<Table 1 is inserted about here>

3.2 Net buying pressure

We follow the previous definition provided within the extant literature (Chordia et al., 2002; Bollen and Whaley, 2004) to measure net buying pressure (NBP) as the difference between the volume of buyer-initiated VIX calls (puts) and the volume of seller-initiated VIX calls (puts) during that period:

$$NBP_t = B_t - S_t, \tag{4}$$

where NBP_t is the net buying pressure at interval t; B_t and S_t are the buyer-initiated volume and seller-initiated volume at interval *t*, respectively. We propose to use the sensitivity measures as the weight in constructing net buying pressure, where the *delta* net buying pressure, formally defined as the difference between the buyer-initiated volume and seller-initiated volume, is multiplied by the absolute value of the VIX option's delta to express exposure in VIX futures. We then scale the net buying pressure by total trading volume of VIX calls (puts) at interval *t.*

Table 2 reports the summary statistics of VIX calls and puts over five minute intervals for the sample period from January 2, 2008 to March 31, 2010, providing a total of 566 trading days. As shown in the table, we find that the mean of NBP has a positive value for five option series in our sample period, and only NBP of ATM calls is negative in the VIX options market. The results show that net buying pressures generally have a positive value in VIX options.

<Table 2 is inserted about here>

3.3 Empirical methodology

This study examines the impact of net buying pressure on implied volatility in the VIX options market. We follow Bollen and Whaley (2004) to carry out the subsequent three regressions using the Newey-West robust correction for standard errors in the coefficients:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBP_t^{ATM,i} + \gamma_4 NBP_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t, \quad (5)$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBP_t^{OTM,i} + \lambda_4 NBP_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t, \quad (6)$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBP_t^{ITM,i} + \delta_4 NBP_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t, \quad (7)$$

where *i* (*j*) represents call (put) option; $\Delta IVoV_t^{moneyness,i}$ refers to the change in the average implied volatility of moneyness VIX call (put) options in interval *t*; *Ret* denotes the average return of VIX futures; and *Vol* is the average dollar trading volume of VIX futures expressed in millions of USD in interval *t*. All variables are calculated across five-minute time intervals.

The above is similar to the setting in Bollen and Whaley (2004) and Kang and Park (2008), for example, when the dependent variable is the change in the average implied volatility of OTM VIX calls (puts), and $NBP_t^{OTM,i}$ and $NBP_t^{ATM,j}$ are net buying pressure of OTM VIX calls (puts) and ATM VIX calls (puts), respectively. Under the limit to arbitrage hypothesis, the change in the average implied volatility is impacted by the net buying pressure of the same moneyness category, while the net buying pressure of ATM VIX options does not influence the change in the average implied volatility. The result shows that option prices are expected to be affected by its trading pressure. The implied volatilities of different option series need not move together as they are primarily affected by option series' own demand. On the other hand, if the information hypothesis is true, then we shall find that the change in the average implied volatility is impacted not only by the net buying pressure of the same moneyness category, but that the net buying pressure of ATM VIX calls (or puts) also impacts the change in the average implied volatility. Overall, the trading activity of investors provides information to the market maker, who continually learns about the underlying asset dynamics and updates prices as a result.

We further note that the lagged changes in average implied volatility are included in the regression so as to have a better understanding of distinguishing the two hypotheses. These coefficients of lagged change in average implied volatility are also expected to be negative and significant under the limit to arbitrage hypothesis, because the temporary impact of net buying pressure infers that the change in average implied volatility will reverse. In this case, the increases in VIX option prices induced by the increases in net buying pressure would be temporary. They revert to the fundamental values as liquidity providers rebalance their inventory positions. On the other hand, if information is already reflected in the price and implied volatility, then changes in implied volatility would be permanent, denoting that these coefficients of lagged change in average implied volatility would be insignificant. The result suggests that no serial correlation in implied volatility changes because trading activities in the VIX options market quickly reflect all information in option prices.

4. EMPIRICAL RESULTS

4.1 The effects of net buying pressure on VIX option prices

The preliminary findings of this study in Table 2 summarize the estimation results for changes in the implied volatility of ATM (OTM and ITM) VIX options reported in Panel A (B and C). The corresponding net buying pressure (that is, γ_3, λ_3, and δ_3) reveals a strong positive and significant impact on the change in average implied volatility. This means that a unit of net buying pressure will increase the average implied volatility by 0.01% to 0.03% in a contemporaneous five-minute interval. On the other hand, the coefficients of net buying pressure of the other options series (that is, γ_4, λ_4, and δ_4), are not statistically significant. In addition to the contemporaneous effects of net buying pressure, the change in average implied volatility in the previous period exhibits a considerable reversal, which means that the change in average implied volatility induced by net buying pressure will disappear in the next period.

Our results imply that the absence of any observable informational effect in the average implied volatility change arises due to net buying pressure. In other words, we find that the limit of the arbitrage effect does prevail against the informational effect in the VIX options market.[9]

<Table 3 is inserted about here>

4.2 The refined NBP: Vega weight adjusted

This section targets to provide further evidence in support of the limit to arbitrage hypothesis in the VIX options market. In the literature, the stock price sensitivity of an option is measured by delta, or the partial derivative of the option value with respect to the underlying stock price. The sensitivity of an option to volatility is measured by vega, or the partial derivative of the option value with respect to return volatility. Compared to delta net buying pressure, we use the sensitivity measured by vega as a weight in constructing vega net buying pressure. We refer to the approach of Whaley (1993), in which the VIX option's vega is:

$$Vega_{call} = Vega_{put} = F_0 e^{-rT} N'(d_1)\sqrt{T} \ . \tag{8}$$

Our paper calculates the VIX options' vega for each option trade using the valuation methodologies and parameter assumptions described above. Here, $N'(\bullet)$ is the normal density function.

We replace the delta net buying pressure with vega net buying pressure to re-examine previous regressions. Similar to the findings in Table 3, Table 4 summarizes the estimation results for changes in the implied volatility of ATM (OTM and ITM) VIX options reported in Panel A (B and C). The corresponding

[9] Kao, Tsai, Wang, and Yen (2018) investigate the relation between trading activity in the VIX derivative markets and changes in the VIX index. They find that the trading activity in VIX options would induce a temporary linkage with VIX changes and investors use VIX options for hedging purposes in response to changes in the VIX.

vega net buying pressure (that is, γ_3, λ_3, and δ_3) shows a significant and positive impact on the change in average implied volatility. This result indicates that a unit of vega net buying pressure will increase the average implied volatility by 0.001% to 0.004% in a contemporaneous five-minute interval. On the other hand, the coefficients of vega net buying pressure of the other option series (that is, γ_4, λ_4, and δ_4), are not statistically significant. In addition to the contemporaneous effects of net buying pressure, the change in average implied volatility in the previous period exhibits a considerable reversal, which means that the change in average implied volatility induced by net buying pressure will disappear in the next period. In summary, our paper examines the impact of intraday trading activity of VIX options on their market prices, finding that the results support the prediction concerning the limit of the arbitrage hypothesis rather than the information hypothesis in the VIX options market.

<Table 4 is inserted about here>

4.3 Intraday trading pattern in VIX options

Figure 1 illustrates the average trading volume in VIX options for each 5-minute interval, Panel A presents the intraday trading pattern of VIX call options, and Panel B presents the intraday trading pattern of VIX put options. We see an obvious U-shaped intraday pattern in the VIX options markets. The trading volume is relatively higher during both the opening and closing periods regardless of VIX call options or VIX put options. Hence, if the trading volumes are influenced by the intraday trading pattern in the options market, then the net buying pressure may be pronounced at the market opening.[10] Consequently, we examine whether am

[10] Chan, Chen, and Lung (2010) find that Net buying pressure in S&P 500 futures options exhibits an intraday pattern.

intraday trading pattern may impact the prior empirical results.

<Figure 1 is inserted about here>

As shown in Table 5, we divide VIX options data into three time groups: open (from 8:30 a.m. to 10:00 a.m.), middle (from 10:00 a.m. to 1:45 p.m.), and close (from 1:45 p.m. to 3:15 p.m.); next, we re-examine previous regressions. Our results show that the coefficients on net buying pressure (γ_3, λ_3, and δ_3) have positive and significant impacts on the change in average implied volatility, but the coefficients of net buying pressure of the other options series (that is, γ_4, λ_4, and δ_4), are not statistically significant. The change in average implied volatility in the previous period exhibits a considerable reversal, which means that the change in average implied volatility induced by net buying pressure will disappear in the next period. Hence, the empirical results support our earlier findings, which is consistent with the limit to arbitrage hypothesis. In addition, our unreported works show that these coefficients are not different from each other in the three groups.[11] The limits to arbitrage between the net buying pressure and the change in implied volatility in VIX options are overall not affected by the pattern in intraday trading volume.

<Table 5 is inserted about here>

4.4 Time interval sampling

For market microstructure features, sampling frequency and sample size of trading volumes may affect options prices. According to earlier findings, the demand for options pushes up implied volatility more easily under high frequency environments, and so we can observe that net buying pressure has a higher impact on the change in

[11] We use the Clogg, Petkova and Haritou (1995) methodology to test whether the difference between the three groups' regression coefficient (that is, γ_3, λ_3, and δ_3) is significantly different from zero. Test results exhibit that the coefficients between the three groups are similar.

implied volatility due to limits to arbitrage. Thus, we go on to examine the effect in the difference of interval periods on the relationship between net buying pressure and change in implied volatility in VIX options.

We re-estimate the regression model using the fifteen-minute interval and forty-five-minute interval, as opposed to the five-minute interval. Table 6 presents the regression tests at selected frequencies for the effect of net buying pressure on the implied volatility of volatility change. In the empirical results, we still find a temporal relationship between the net buying pressure of VIX options and changes in implied volatility of volatility from VIX options prices. In the low-frequency part of our sample (15 minutes and 45 minutes), the impact of the corresponding net buying pressure on the change in average implied volatility is gradually weakened. The results also show that the liquidity provider has the capacity to provide more liquidity in low-frequency environments.

<Table 6 is inserted about here>

4.5 The impacts of net buying pressure on the next-day delta-hedged option returns

Option prices would be influenced by investors' demand pressures due to market makers being capital-constrained and unable to perfectly hedge their inventories (Bollen and Whaley, 2004; Garleanu, Pedersen, and Poteshman, 2009). Thus, in this subsection, we test the impact of net buying pressure on the next-day delta-hedged option returns in the VIX options market.

We refer to Park (2015) to compute delta-hedged returns that that immune to the VIX futures price risk, rebalancing at each discrete time point of the period $[t, t+\tau]$. The discrete delta-hedged call option gain over the period $[t, t+\tau]$ can be represented as follows:

$$R^{o}_{t,t+\tau,k} = \frac{O_{t+\tau,k} - O_{t,k} - \sum_{n=0}^{N-1} \Delta_{t_{n,k}} (F_{t_{n+1,k}} - F_{t_{n,k}})}{O_{t,k}} - \frac{r_t^f N}{365} \tag{9}$$

where, $O_{t+\tau,k}$ donate the VIX option price in a moneyness category *k* at day $t+\tau$; F_{t_n} indicates the VIX futures price at time t_n; Δ_{t_n} refers to the corresponding option delta at time t_n; r_t^f is the risk-free interest rate at time *t*. Referring to the study of Christoffersen, Goyenko, Jacobs and Karoui (2018), we also include VIX futures' dollar trading volume, VIX options' average bid-ask spread and average trading volume as control variables to study the effect of net buying pressure on VIX option returns. The statistical significance is computed by Newey and West (1987) robust t-statistics with an optimal lag period.

Table 7 shows the impact of net buying pressure on the next-day delta-hedged returns in the VIX options market. It is clearly seen that the coefficients of net buying pressure are significantly negative for both VIX call and put option returns, regardless of which moneyness is considered. In other words, higher net buying pressure of VIX options lowers the next-day delta-hedged returns of VIX options, indicating that option prices are more expensive as the market faces serious trading pressure. Our results provide additional evidence to support for theoretical predictions of Christoffersen et al. (2018), arguing that market makers are trying to correct their heavy selling positions by rising up the following option prices.

<Table 7 is inserted about here>

4.6 Limits to arbitrage and the implied volatility level of VIX options

Our earlier analyses clearly present that net buying pressure, which is associated with limits to arbitrage, affects the pricing of VIX options. To verify the robustness of our earlier empirical results, our paper follows up with previously documented evidence of limits to arbitrage in the financial markets to examine the impact of limits to arbitrage on VIX options prices. Based on the Duan and Wei (2009) framework, our goal is to identify whether the implied volatility level of the VIX options is related to the proxies of limits to arbitrage. We follow the methodology of Duan and Wei (2009) to estimate the level of the implied volatility curve in the VIX options market. In the first part of the equation, we collect all moneyness buckets of VIX options in a one-day period and employ the following regression (10), with the intercept being extracted as the level of the implied volatility:

$$\sigma_{k,t}^{imvol} - \sigma_t^{hisvol} = \alpha_{0,t} + \alpha_{1,t}(y_{k,t} - \bar{y}_t) + \varepsilon_{k,t},\ k = 1, 2, ..., n, \tag{10}$$

where $\sigma_{k,t}^{imvol}$ denotes all observations of implied volatility in day *t*; σ_t^{hisvol} is the annualized return volatility of the VIX futures over the most recent sixty trading days; *n* is the number of VIX options in a particular maturity category for day *t*; $y_{k,t}$ is the moneyness measured by the strike price divided by the future price ($K_{k,t} / F_{k,t}$), and $\bar{y}_t$ is the sample average of $y_{k,t}$. Moreover, $\alpha_{0,t}$ and $\alpha_{1,t}$ are measures for the level and the slope of the implied volatility in day *t*.

In the second part, we carry out the following regression using the Newey–West robust correction for standard errors in the coefficients:

$$\alpha_{0,t} = \gamma_{0,t} + \gamma_{1,t} LTA_t^i + \varepsilon_t, \tag{11}$$

where $\alpha_{0,t}$ denotes the intercept from the first part regressions as the dependent variable, and LTA_t^i are various proxies for arbitrage risk, which we adopt as follows: First, we follow Chou, Huang and Yang (2013) and use two measures of implementation risk (transaction costs), bid–ask spread and trading volume, separately defined as VIX options' average bid-ask spread (2*(Ask - Bid)/(Ask + Bid)) and average trading volume (the day-end closing price multiplied by the day-end total shares traded, in millions of dollars).

Furthermore, we employ the Google search volume index as the measure for noise-trader risk. Following Da, Engelberg and Gao (2015), we use Financial and Economic Attitudes Revealed (FEARS) by search proxy for investor sentiment as noise-trader risk. Furthermore, we also use VIX Search to measure noise-trader risk, defined by the Google search volume index on the key word "VIX". Thus, increased investor attention or sentiment creates positive pressure on prices.

Finally, our analysis includes both the Libor-Tbill and Libor-Repo spreads, which are proxies for funding liquidity. We use Ted spread and Libor-Repo spread as our measures of funding liquidity, which are consistent with the previous study by Bhanot and Guo (2012). Brunnermeier and Pedersen (2009) suggest that the level of funding liquidity can be proxied by the Ted spread (the difference between three-month Libor and three-month T-bill rates) and the Libor-Repo spread (the difference between three-month Libor and three-month Repo rates) at which an arbitrageur can borrow in case the position requires collateralized funding. Thus, when investors may force more expensive hedging costs, resulting in limits to arbitrage is severe in VIX options market.

Table 8 shows the relationship between the proxies of limits to arbitrage and the implied volatility level of the VIX options. For implied volatility level of the VIX call options reported in Panel A, the coefficients on FEARS and VIX Search are positive and significant on the level of implied volatility in Models (1) and (2), indicating that an increase in noise-trader risk creates positive pressure on the implied volatility level of call options. In Models (3) and (4), only the coefficient of

Libor-Repo Spread is significantly positively correlated with the VIX options implied volatility level. These results show that investors may face more expensive hedging costs and that the level of implied volatility will increase with severe limits to arbitrage, which would mean that the limits to arbitrage will affect the pricing of VIX options.

Our result further shows that the coefficient on bid-ask spread is negative and significant, and that the coefficient on trading volume is significantly positively related to implied volatility level. These results suggest that VIX options become more expensive with large net buying pressure, lower transaction cost, and greater option liquidity, which is a result that is similar to Chou, Chung, Hsiao and Wang (2011).[12]

We now turn to the result of the implied volatility level of VIX put options. Once again, the findings are consistent with those reported in Panel A of Table 8 and support the empirical result in earlier tables, displaying that limits to arbitrage do affect the pricing of VIX options.

<Table 8 is inserted about here>

4.7 Trading profits

Our earlier analyses clearly present that the limit of the arbitrage effect does prevail against the informational effect in the VIX options market. Given these findings, a question arises as to whether intraday prices of VIX futures are affected when liquidity providers face buying or selling pressure in the VIX options market. Hu (2014) shows that when option investors execute options trades, options liquidity

[12] Chou et al. (2011) find that options become more expensive when the options market is less illiquid, thus supporting the "illiquidity premium" hypothesis proposed by Amihud and Mendelson (1986).

providers (such as market makers) gain risk exposures to the underlying price movement and return volatility. The author further illustrates that liquidity providers facing inventory control problems will not unload inventory immediately when liquidity in the options market is not high enough; thus, liquidity providers need to hedge the underlying price risk by transacting in the underlying market. In doing so, options liquidity providers perform delta hedging transactions in the underlying asset market, leading to changes in the underlying asset price. Thus, we attempt to analyze the VIX future returns from the impact of limits to arbitrage on prices in the VIX options market and construct strategies from net buying pressure of VIX options.

We aggregate the trading volumes of VIX call and put options and also use the corresponding option deltas as the weights in constructing the net buying pressure, in order to express demand in equivalent units of VIX futures. The final net buying pressure is scaled by the open interest of VIX futures on each day and by 10.[13]

Our strategy for estimating the trading performance of VIX futures is that a value of option-induced net buying pressure in the previous day is higher (lower) than maximum (minimum) value of the past k-day (k= 5, 10, and 15) and denotes a higher hedging demand in the VIX futures market. We then long (short) a VIX futures contract at the opening price and realize the profits on the closing price. We define the abnormal returns as the realized profits minus daily S&P500 index change.[14] The annualized abnormal returns denote the performance of this strategy. We report the average abnormal returns (ARs) by different criteria. Table 9 reports

[13] We estimate overall net VIX futures exposure induced by VIX call and put options to evaluate the impact of net buying pressure of VIX options on VIX futures. The contract multiplier is $1,000 for each VIX futures contract, whilst it is $100 for each VIX options contract. Thus, the net buying pressure is divided by 10 here.
[14] We use closing price minus opening price of S&P500 index as our daily price change.

the average value for the long (Panel A) and short (Panel B) strategies.

As the table shows, during the sample period both long and short strategies exhibit significant excess returns for VIX futures. Furthermore, long strategies slightly outperform short strategies, especially in 5-day and 10-day strategies. This finding is consistent with Table 1, which notes that bullish trading activities (buyer-initiated calls and seller-initiated puts) are more prevalent than bearish trading activities (seller-initiated calls and buyer-initiated puts) in the VIX options market. The returns of VIX futures on the long (short) strategies decrease (increase) almost monotonically across different criteria. The long strategies have an annualized excess return between 10.09% and 5.08%, while the short strategies have an annualized excess return between -8.37% and -0.5.13%. The excess return is significant at the 5% and 10% levels. The results suggest that liquidity providers transfer their exposure from the VIX options market to the VIX futures market through their hedging when large net buying pressures are initiated in the VIX options market.

<Table 9 is inserted about here>

5. CONCLUSIONS

This paper investigates the impact of intraday trading activity of VIX options on their market prices. Our study focuses on intraday data to gain a better understanding of the effect of net buying pressure in the VIX options market. The results show a temporal relationship between net buying pressure of VIX options and changes in implied volatility of VIX options. We further study the impacts of the net buying pressure on the next-day delta-hedged option returns, and demonstrate a negative relationship between the net buying pressure and VIX option returns, representing that intraday trading pressure in the VIX options market slightly affects option pricing.

When there are serious limits to arbitrage in the market, we find the level of the implied volatility curve of VIX options rises up. Furthermore, according to the point view of Hu (2014), options liquidity providers would, via hedging activities, affect the underlying asset market; thus, we capture the impact of net buying pressure of VIX options on VIX futures by building a trading strategy in the VIX futures market. This implies that trading activity in the VIX options market has an impact on VIX futures prices. Overall, these results are likely to be consistent with the implications of the limits-to-arbitrage hypothesis (Shleifer and Vishny, 1997; Gârleanu et al., 2009).

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Table 1 Summary statistics of the VIX options across moneyness

This table presents the summary statistics of the VIX calls and puts based upon the circumscription of each moneyness category and lists the moneyness, the corresponding delta ranges, and the category numbers of options in our sample, with the sample period running from January 2, 2008 to March 31, 2010. Options with absolute deltas below 0.05 and above 0.95 are excluded. Panel A reports the average trading volume of buyer- (seller-) initiated and unclassified trades across various categories of moneyness for call and put options. Panel B reports the amount of trading volume accounting for the proportion of total trading volume of buyer- (seller-) initiated and unclassified trades across various categories of moneyness for call and put options. Moneyness is defined as the corresponding delta ranges of options in our sample.

Panel A: Average trading volume in five minutes

VIX Calls	1	2	3
Category	In-the-money	At-the-money	Out-of-the-money
Moneyness	(0.95≥delta>0.65)	(0.65≥delta>0.35)	(0.35≥delta>0.05)
Buy	39.5029	64.1737	116.8053
Sell	39.7927	59.0304	91.8091
Unclassified	0.5774	0.5516	1.5413
VIX Puts	1	2	3
Category	Out-of-the-money	At-the-money	In-the-money
Moneyness	(-0.05≥delta>-0.35)	(-0.35≥delta>-0.65)	(-0.65≥delta>-0.95)
Buy	89.0547	41.6002	18.9144
Sell	78.7709	42.0961	16.3662
Unclassified	1.3040	1.4844	0.3862

Panel B: Proportion of total

VIX Calls	1	2	3
Category	In-the-money	At-the-money	Out-of-the-money
Moneyness	(0.95≥delta>0.65)	(0.65≥delta>0.35)	(0.35≥delta>0.05)
Buy	5.61%	9.12%	16.60%
Sell	5.65%	8.39%	13.04%
Unclassified	0.08%	0.08%	0.22%
VIX Puts	1	2	3
Category	Out-of-the-money	At-the-money	In-the-money
Moneyness	(-0.05≥delta>-0.35)	(-0.35≥delta>-0.65)	(-0.65≥delta>-0.95)
Buy	12.65%	5.91%	2.69%
Sell	11.19%	5.98%	2.33%
Unclassified	0.19%	0.21%	0.05%

Table 2 Descriptive statistics

This table reports the summary statistics of VIX calls and puts over five-minute intervals for the sample period from January 2, 2008 to March 31, 2010, providing a total of 566 trading days. Average Implied Volatility of Volatility is calculated as mean implied volatility of VIX options; Average Implied Volatility of Volatility Change is the mean change in implied volatility; Net Buying Pressure is calculated as the ratio of the buyer-initiated less the seller-initiated trade volumes times the absolute value of the option's delta to total trade volume.

Panel A: VIX Calls

	In-the-money (ITM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	73.9248	16.6909	57.7463	70.3107	95.5729
Avg. IVoV. Change (%)	-0.0001	6.6422	-5.4087	0.0000	5.3174
Net Buying Pressure	0.0025	0.5079	-0.7854	0.0000	0.7895
	At-the-money (ATM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	78.1289	16.1088	62.2393	74.7650	98.7509
Avg. IVoV. Change (%)	-0.0007	6.7642	-5.4182	0.0000	5.3793
Net Buying Pressure	-0.0031	0.3377	-0.5037	0.0000	0.4956
	Out-of-the-money (OTM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	84.5966	15.5792	68.5718	81.4592	105.3327
Avg. IVoV. Change (%)	0.0000	7.9590	-7.8010	0.0000	7.8155
Net Buying Pressure	0.0022	0.1401	-0.1905	0.0000	0.1928

Panel B: VIX Puts

	In-the-money (ITM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	84.7750	16.0176	68.0077	81.8833	106.2778
Avg. IVoV. Change (%)	-0.0005	5.4854	-1.5613	0.0000	1.6123
Net Buying Pressure	0.0054	0.3827	-0.6668	0.0000	0.6856
	At-the-money (ATM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	78.3593	15.9312	62.1298	75.2099	98.9397
Avg. IVoV. Change (%)	-0.0007	5.9113	-2.7149	0.0000	2.7445
Net Buying Pressure	0.0026	0.2868	-0.4506	0.0000	0.4537
	Out-of-the-money (OTM)				
	Mean	Std.	P10	Median	P90
Avg. IVoV. (%)	73.6092	15.9013	58.0715	70.1019	94.1429
Avg. IVoV. Change (%)	0.0002	6.7543	-5.5106	0.0000	5.5473
Net Buying Pressure	0.0028	0.1338	-0.1804	0.0000	0.1861

Table 3 The impact of net buying pressure on the implied volatility of volatility change in 5-minute intervals

This table presents the regression tests for the net buying pressure on the implied volatility of volatility change. The regression specification is formulated as follows:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBP_t^{ATM,i} + \gamma_4 NBP_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBP_t^{OTM,i} + \lambda_4 NBP_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBP_t^{ITM,i} + \delta_4 NBP_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t,$$

where $\Delta IVoV_t^{moneyness,i}$ is the change in the average implied volatility of VIX options over 5-minute interval t; *Ret* is the average return of VIX futures over 5-minute interval t; *Vol* is average dollar trading volume of VIX futures over 5-minute interval t; and $NBP_t^{moneyness,i}$ and $NBP_t^{moneyness,j}$ denote the net buying pressure of VIX options over 5-minute interval t. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The sample period is from January 2, 2008 to March 31, 2010.

Panel A: $\Delta IVoV^{ATM}$

i	j	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	n	Adj. R^2
$NBP^{ATM,Call}$	$NBP^{ATM,Put}$	0.0000	0.4562*	0.0000	0.0113***	-0.0005	-0.3128***	45846	0.1012
		(0.23)	(1.72)	(-0.08)	(9.31)	(-0.41)	(-38.88)		
$NBP^{ATM,Put}$	$NBP^{ATM,Call}$	0.0000	0.1143	-0.0001	0.0126***	0.0013	-0.2104***	45846	0.0478
		(-0.16)	(0.45)	(-0.23)	(8.32)	(1.54)	(-22.74)		

Panel B: $\Delta IVoV^{OTM}$

i	j	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	n	Adj. R^2
$NBP^{OTM,Call}$	$NBP^{ATM,Call}$	0.0000	0.4111	-0.0003	0.0298***	0.0007	-0.3523***	45846	0.1270
		(-0.04)	(1.48)	(-0.53)	(9.51)	(0.70)	(-46.54)		
$NBP^{OTM,Call}$	$NBP^{ATM,Put}$	0.0000	0.4160	-0.0003	0.0299***	-0.0007	-0.3522***	45846	0.1270
		(-0.04)	(1.50)	(-0.53)	(9.51)	(-0.57)	(-46.55)		
$NBP^{OTM,Put}$	$NBP^{ATM,Call}$	-0.0002	0.8532***	0.0005	0.0310***	-0.0009	-0.3311***	45846	0.1134
		(-1.08)	(3.55)	(1.06)	(10.53)	(-1.03)	(-43.01)		
$NBP^{OTM,Put}$	$NBP^{ATM,Put}$	-0.0002	0.7788***	0.0005	0.0311***	-0.0017	-0.3311***	45846	0.1135
		(-1.03)	(3.27)	(1.06)	(10.57)	(-1.56)	(-43.01)		

Table 3 (continued)

Panel C: $\Delta IVoV^{ITM}$

i	j	δ_0	δ_1	δ_2	δ_3	δ_4	δ_5	n	Adj. R^2
$NBP^{ITM,Call}$	$NBP^{ATM,Call}$	0.0001	0.0429	-0.0008	0.0099***	-0.0008	-0.2852***	45846	0.0870
		(0.77)	(0.16)	(-1.38)	(11.78)	(-0.92)	(-31.97)		
$NBP^{ITM,Call}$	$NBP^{ATM,Put}$	0.0001	0.0301	-0.0008	0.0099***	0.0006	-0.2852***	45846	0.0870
		(0.77)	(0.11)	(-1.37)	(11.79)	(0.55)	(-31.97)		
$NBP^{ITM,Put}$	$NBP^{ATM,Call}$	-0.0001	0.2109	0.0004	0.0116***	0.0013	-0.1878***	45846	0.0414
		(-0.79)	(0.93)	(0.76)	(9.57)	(1.62)	(-18.95)		
$NBP^{ITM,Put}$	$NBP^{ATM,Put}$	-0.0001	0.2650	0.0004	0.0116***	0.0003	-0.1878***	45846	0.0413
		(-0.82)	(1.17)	(0.75)	(9.55)	(0.34)	(-18.96)		

Table 4 The impact of net buying pressure for Vega weighted on the implied volatility of volatility change in 5-minute intervals

This table presents the regression tests for the net buying pressure with vega weighted on the implied volatility of volatility change. The regression specification is formulated as follows:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBPV_t^{ATM,i} + \gamma_4 NBPV_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBPV_t^{OTM,i} + \lambda_4 NBPV_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBPV_t^{ITM,i} + \delta_4 NBPV_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t,$$

where $\Delta IVoV_t^{moneyness,i}$ is the change in the average implied volatility of VIX options over 5-minute interval t, *Ret* is the average return of VIX futures over 5-minute interval t, *Vol* is average dollar trading volume of VIX futures over 5-minute interval t; and $NBPV_t^{moneyness,i}$ and $NBPV_t^{moneyness,j}$ denote the Vega weighted net buying pressure of VIX options over 5-minute interval t. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The sample period is from 2 January 2008 to 31 March 2010.

Panel A: $\Delta IVoV^{ATM}$

i	*j*	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	n	Adj. R^2
$NBPV^{ATM,Call}$	$NBPV^{ATM,Put}$	0.0000	0.5018*	-0.0001	0.0013***	-0.0001	-0.3131***	45846	0.1007
		(0.28)	(1.88)	(-0.15)	(7.02)	(-0.55)	(-38.94)		
$NBPV^{ATM,Put}$	$NBPV^{ATM,Call}$	0.0000	0.0673	0.0000	0.0015***	0.0002	-0.2106***	45846	0.0471
		(0.02)	(0.27)	(-0.11)	(5.81)	(1.31)	(-22.75)		

Panel B: $\Delta IVoV^{OTM}$

i	*j*	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	n	Adj. R^2
$NBPV^{OTM,Call}$	$NBPV^{ATM,Call}$	0.0000	0.4515	-0.0003	0.0021***	0.0001	-0.3523***	45846	0.1265
		(0.14)	(1.62)	(-0.63)	(7.19)	(0.45)	(-46.55)		
$NBPV^{OTM,Call}$	$NBPV^{ATM,Put}$	0.0000	0.4324	-0.0003	0.0021***	-0.0002	-0.3522***	45846	0.1265
		(0.15)	(1.55)	(-0.64)	(7.18)	(-1.02)	(-46.55)		
$NBPV^{OTM,Put}$	$NBPV^{ATM,Call}$	-0.0001	0.8626***	0.0006	0.0025***	-0.0002	-0.3313***	45846	0.1136
		(-0.77)	(3.59)	(1.19)	(8.98)	(-1.26)	(-43.02)		
$NBPV^{OTM,Put}$	$NBPV^{ATM,Put}$	-0.0001	0.8080***	0.0006	0.0025***	-0.0001	-0.3312***	45846	0.1136
		(-0.74)	(3.40)	(1.18)	(9.00)	(-0.45)	(-42.99)		

Table 4 (continued)

Panel C: $\Delta IVoV^{ITM}$

i	j	δ_0	δ_1	δ_2	δ_3	δ_4	δ_5	n	Adj. R^2
$NBPV^{ITM,Call}$	$NBPV^{ATM,Call}$	0.0001	0.2186	-0.0008	0.0022***	-0.0001	-0.2852***	45846	0.0841
		(0.82)	(0.81)	(-1.46)	(7.31)	(-0.52)	(-31.94)		
$NBPV^{ITM,Call}$	$NBPV^{ATM,Put}$	0.0001	0.2361	-0.0008	0.0022***	0.0002	-0.2852***	45846	0.0841
		(0.82)	(0.87)	(-1.45)	(7.34)	(1.22)	(-31.95)		
$NBPV^{ITM,Put}$	$NBPV^{ATM,Call}$	-0.0001	0.1472	0.0004	0.0032***	0.0001	-0.1873***	45846	0.0394
		(-0.46)	(0.65)	(0.82)	(6.29)	(1.17)	(-18.88)		
$NBPV^{ITM,Put}$	$NBPV^{ATM,Put}$	-0.0001	0.2601	0.0003	0.0117***	0.0003	-0.1879***	45846	0.0414
		(-0.78)	(1.15)	(0.70)	(9.56)	(0.29)	(-18.95)		

Table 5 The impact of net buying pressure on the implied volatility of volatility change in different trading hours

This table presents the regression tests for the net buying pressure on the implied volatility of volatility change. To avoid intraday trading affecting the result, we divide the trading hours into three time groups: open (from 8:30 a.m. to 10:00 a.m.), middle (from 10:00 a.m. to 1:45 p.m.), and close (from 1:45 p.m. to 13:15 p.m.) for each trading day. The sample period is from 2 January 2008 to 31 March 2010. The regression specification is formulated as follows:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBP_t^{ATM,i} + \gamma_4 NBP_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBP_t^{OTM,i} + \lambda_4 NBP_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBP_t^{ITM,i} + \delta_4 NBP_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t,$$

where $\Delta IVoV_t^{moneyness,i}$ is the change in the average implied volatility of VIX options over 5-minute interval t, *Ret* is the average return of VIX futures over 5-minute interval t, *Vol* is average dollar trading volume of VIX futures over 5-minute interval t; and $NBP_t^{moneyness,i}$ and $NBP_t^{moneyness,j}$ denote the net buying pressure of VIX options over 5-minute interval t. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The sample period is from 2 January 2008 to 31 March 2010.

Panel A: $\Delta IVoV^{ATM}$

		Open (8:30 a.m. - 10:00 a.m.)			Middle (10:00 a.m. - 1:45 p.m.)			Close (1:45 p.m. - 3:15 p.m.)		
i	j	γ_3	γ_4	γ_5	γ_3	γ_4	γ_5	γ_3	γ_4	γ_5
$NBP^{ATM,Call}$	$NBP^{ATM,Put}$	0.0127***	-0.0009	-0.3408***	0.0108***	-0.0002	-0.2850***	0.0110***	-0.0008	-0.3418***
		(5.47)	(-0.41)	(-22.48)	(6.55)	(-0.11)	(-25.12)	(4.34)	(-0.37)	(-19.84)
$NBP^{ATM,Put}$	$NBP^{ATM,Call}$	0.0103***	-0.0002	-0.2486***	0.0143***	0.0029	-0.1868***	0.0119***	-0.0006	-0.2199***
		(4.10)	(-0.11)	(-13.88)	(6.40)	(1.59)	(-14.08)	(3.90)	(-0.36)	(-13.20)

Panel B: $\Delta IVoV^{OTM}$

		Open (8:30 a.m. - 10:00 a.m.)			Middle (10:00 a.m. - 1:45 p.m.)			Close (1:45 p.m. - 3:15 p.m.)		
i	j	λ_3	λ_4	λ_5	λ_3	λ_4	λ_5	λ_3	λ_4	λ_5
$NBP^{OTM,Call}$	$NBP^{ATM,Call}$	0.0298***	0.0030	-0.3726***	0.0282***	-0.0005	-0.3264***	0.0337***	0.0011	-0.3956***
		(5.09)	(1.49)	(-27.24)	(6.46)	(-0.32)	(-37.07)	(5.25)	(0.51)	(-22.06)
$NBP^{OTM,Call}$	$NBP^{ATM,Put}$	0.0300***	-0.0018	-0.3727***	0.0282***	-0.0006	-0.3264***	0.0338***	0.0001	-0.3954***
		(5.14)	(-0.72)	(-27.28)	(6.45)	(-0.33)	(-37.07)	(5.26)	(0.02)	(-22.04)
$NBP^{OTM,Put}$	$NBP^{ATM,Call}$	0.0290***	-0.0003	-0.3629***	0.0295***	-0.0016	-0.3105***	0.0367***	0.0002	-0.3475***
		(4.99)	(-0.18)	(-23.96)	(7.00)	(-1.37)	(-28.37)	(6.45)	(0.11)	(-23.19)
$NBP^{OTM,Put}$	$NBP^{ATM,Put}$	0.0292***	-0.0023	-0.3629***	0.0296***	-0.0005	-0.3105***	0.0368***	-0.0036	-0.3476***
		(5.03)	(-1.18)	(-23.98)	(7.01)	(-0.32)	(-28.37)	(6.46)	(-1.34)	(-23.19)

Table 5 (continued)

Panel C: $\Delta IVoV^{ITM}$

i	j	Open (8:30 a.m. - 10:00 a.m.) δ_3	δ_4	δ_5	Middle (10:00 a.m. - 1:45 p.m.) δ_3	δ_4	δ_5	Close (1:45 p.m. - 3:15 p.m.) δ_3	δ_4	δ_5
$NBP^{ITM,Call}$	$NBP^{ATM,Call}$	0.0092***	0.0006	-0.2907***	0.0097***	-0.0009	-0.2857***	0.0111***	-0.0020	-0.2765***
		(5.72)	(0.33)	(-15.06)	(8.13)	(-0.72)	(-21.14)	(6.93)	(-1.04)	(-19.66)
$NBP^{ITM,Call}$	$NBP^{ATM,Put}$	0.0093***	0.0048	-0.2906***	0.0097***	-0.0001	-0.2857***	0.0110***	-0.0032	-0.2761***
		(5.82)	(1.06)	(-15.07)	(8.12)	(-0.08)	(-21.13)	(6.87)	(-1.59)	(-19.65)
$NBP^{ITM,Put}$	$NBP^{ATM,Call}$	0.0105***	0.0013	-0.1890***	0.0123***	0.0013	-0.1667***	0.0119***	0.0011	-0.2308***
		(4.72)	(0.79)	(-9.85)	(6.87)	(1.26)	(-12.32)	(4.73)	(0.63)	(-10.25)
$NBP^{ITM,Put}$	$NBP^{ATM,Put}$	0.0104***	0.0027	-0.1891***	0.0123***	-0.0002	-0.1667***	0.0119***	-0.0012	-0.2309***
		(4.70)	(1.32)	(-9.89)	(6.85)	(-0.16)	(-12.32)	(4.73)	(-0.58)	(-10.24)

Table 6 The impact of net buying pressure on the implied volatility of volatility change in different time intervals

This table presents the regression tests at selected frequencies for the net buying pressure on the implied volatility of volatility change. The regression specification is formulated as follows:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBP_t^{ATM,i} + \gamma_4 NBP_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBP_t^{OTM,i} + \lambda_4 NBP_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t,$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBP_t^{ITM,i} + \delta_4 NBP_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t,$$

where $\Delta IVoV_t^{moneyness,i}$ is the change in the average implied volatility of VIX options over 15-minute interval t, *Ret* is the average return of VIX futures over 15-minute interval t, *Vol* is average dollar trading volume of VIX futures over 15-minute interval t; and $NBP_t^{moneyness,i}$ and $NBP_t^{moneyness,j}$ denote the net buying pressure of VIX options over 15-minute interval t. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The sample period is from 2 January 2008 to 31 March 2010.

Panel A: $\Delta IVoV^{ATM}$

		5-minute interval			15-minute interval			45-minute interval		
i	j	γ_3	γ_4	γ_5	γ_3	γ_4	γ_5	γ_3	γ_4	γ_5
$NBP^{ATM,Call}$	$NBP^{ATM,Put}$	0.0113***	-0.0005	-0.3128***	0.0079***	0.0017	-0.3667***	0.0074***	0.0006	-0.4060***
		(9.31)	(-0.41)	(-38.88)	(5.04)	(1.09)	(-36.27)	(3.24)	(0.31)	(-19.14)
$NBP^{ATM,Put}$	$NBP^{ATM,Call}$	0.0126***	0.0013	-0.2104***	0.0119***	0.0021	-0.3175***	0.0076***	-0.0023	-0.3728***
		(8.32)	(1.54)	(-22.74)	(6.36)	(1.42)	(-24.47)	(2.68)	(-0.90)	(-20.67)

Panel B: $\Delta IVoV^{OTM}$

		5-minute interval			15-minute interval			45-minute interval		
i	j	λ_3	λ_4	λ_5	λ_3	λ_4	λ_5	λ_3	λ_4	λ_5
$NBP^{OTM,Call}$	$NBP^{ATM,Call}$	0.0298***	0.0007	-0.3523***	0.0205***	0.0006	-0.4207***	0.0136**	0.0003	-0.3913***
		(9.51)	(0.70)	(-46.54)	(4.74)	(0.45)	(-42.17)	(2.07)	(0.17)	(-25.05)
$NBP^{OTM,Call}$	$NBP^{ATM,Put}$	0.0299***	-0.0007	-0.3522***	0.0205***	-0.0002	-0.4207***	0.0137**	0.0016	-0.3909***
		(9.51)	(-0.57)	(-46.55)	(4.75)	(-0.15)	(-42.15)	(2.11)	(0.78)	(-25.01)
$NBP^{OTM,Put}$	$NBP^{ATM,Call}$	0.0310***	-0.0009	-0.3311***	0.0189***	-0.0001	-0.3968***	0.0106**	-0.0013	-0.4112***
		(10.53)	(-1.03)	(-43.01)	(5.13)	(-0.06)	(-27.25)	(2.05)	(-0.72)	(-22.10)
$NBP^{OTM,Put}$	$NBP^{ATM,Put}$	0.0311***	-0.0017	-0.3311***	0.0190***	-0.0014	-0.3968***	0.0108**	-0.0019	-0.4112***
		(10.57)	(-1.56)	(-43.01)	(5.14)	(-1.00)	(-27.25)	(2.10)	(-1.04)	(-22.10)

Table 6 (continued)

Panel C: $\Delta IVoV^{ITM}$

i	j	5-minute interval			15-minute interval			45-minute interval		
		δ_3	δ_4	δ_5	δ_3	δ_4	δ_5	δ_3	δ_4	δ_5
$NBP^{ITM,Call}$	$NBP^{ATM,Call}$	0.0099***	-0.0008	-0.2852***	0.0072***	-0.0004	-0.3738***	0.0072***	-0.0008	-0.4196***
		(11.78)	(-0.92)	(-31.97)	(6.38)	(-0.27)	(-28.35)	(4.49)	(-0.36)	(-22.77)
$NBP^{ITM,Call}$	$NBP^{ATM,Put}$	0.0099***	0.0006	-0.2852***	0.0072***	0.0010	-0.3739***	0.0071***	-0.0024	-0.4198***
		(11.79)	(0.55)	(-31.97)	(6.39)	(0.66)	(-28.36)	(4.46)	(-1.20)	(-22.75)
$NBP^{ITM,Put}$	$NBP^{ATM,Call}$	0.0116***	0.0013	-0.1878***	0.0104***	0.0009	-0.2517***	0.0081***	0.0008	-0.3245***
		(9.57)	(1.62)	(-18.95)	(6.86)	(0.60)	(-16.67)	(3.70)	(0.31)	(-16.62)
$NBP^{ITM,Put}$	$NBP^{ATM,Put}$	0.0116***	0.0003	-0.1878***	0.0104***	0.0003	-0.2517***	0.0081***	0.0006	-0.3245***
		(9.55)	(0.34)	(-18.96)	(6.85)	(0.16)	(-16.67)	(3.68)	(0.23)	(-16.62)

Table 7 The impact of net buying pressure on the next-day delta-hedged option returns

The table presents the regression results of delta-hedged option returns on the corresponding net buying pressure and control variables. The sample period is from 2 January 2008 to 31 March 2010 on a daily basis. *Volume* is average million dollar trading volume of VIX futures for day t; Bid-Ask Spread and Trading Volume are VIX options' average bid-ask spread and average trading volume for day t, separately. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

	Call option returns			Put option returns		
	ITM	ATM	OTM	ITM	ATM	OTM
Constant	-0.0192**	-0.0325*	-0.0637**	-0.0025	-0.0214	-0.0094
	(-2.20)	(-1.72)	(-2.17)	(-0.42)	(-1.51)	(-0.57)
Net Buying Pressure	-0.0009*	-0.0080*	-0.0926**	-0.0002**	-0.0043*	-0.0046*
	(-1.73)	(-1.94)	(-2.00)	(-2.07)	(-1.82)	(-1.80)
Volume	0.0005*	0.0013*	0.0025**	0.0007**	0.0007*	0.0003*
	(1.66)	(1.90)	(2.19)	(2.05)	(1.75)	(1.78)
Bid-Ask Spread	0.1238*	0.2006	0.1470*	0.2760*	0.1183*	0.1005
	(1.76)	(0.95)	(1.78)	(1.72)	(1.66)	(1.15)
Trading Volume	0.0002	0.1900	0.9110*	0.0434	0.1940	0.1120*
	(1.03)	(1.32)	(1.92)	(1.02)	(1.56)	(1.74)
N	565	565	565	565	565	565
Adj. R^2	0.0278	0.0410	0.0597	0.0331	0.0344	0.0038

Table 8 The arbitrage risk on the VIX option implied volatility level

The table presents the regression results of the VIX option implied volatility levels on the limits to arbitrage measures. The sample period is from 2 January 2008 to 31 March 2010 on a daily basis. FEARS denotes the Financial and Economic Attitudes Revealed by Search proxy for investor sentiment; VIX Search is the Google search volume index on the key word "VIX" for day *t*; Libor Repo Spread denotes the difference between 3-month Libor rate and 3-month repo rate for day *t*; Ted Spread denotes the difference between 3-month Libor rate and 3-month T-bill rate for day *t*; Bid-Ask Spread and Trading Volume are VIX options' average bid-ask spread and average trading volume, separately. The *t*-statistic based on the Newey-West heteroskedasticity and autocorrelation consistent standard errors are in parentheses. Superscripts *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Panel A: VIX Calls

	Implied Volatility Level					
Constant	0.3854***	0.2299***	0.3701***	0.3820***	0.6786***	0.3708***
	(12.94)	(9.16)	(65.32)	(23.93)	(16.67)	(30.90)
FEARS	0.0164**					
	(1.97)					
VIX Search		0.0044***				
		(6.26)				
Libor Repo Spread			0.0195***			
			(2.60)			
TED Spread				0.0035		
				(0.18)		
Bid-Ask Spread					-3.1352***	
					(-7.03)	
Trading Volume						0.0002*
						(1.84)
n	566	566	566	566	566	566
Adj. R^2	0.0012	0.1536	0.0213	-0.0011	0.1863	0.0295

Panel B: VIX Puts

	Implied Volatility Level					
Constant	0.3390***	0.1821***	0.3246***	0.3359***	0.5600***	0.3207***
	(31.60)	(6.96)	(53.77)	(19.66)	(17.06)	(26.89)
FEARS	0.0188*					
	(1.81)					
VIX Search		0.0044***				
		(6.27)				
Libor Repo Spread			0.0184***			
			(2.37)			
TED Spread				0.0033		
				(0.16)		
Bid-Ask Spread					-2.1644***	
					(-7.43)	
Trading Volume						0.0004***
						(2.62)
n	566	566	566	566	566	566
Adj. R^2	0.0018	0.1459	0.0173	-0.0012	0.2017	0.0223

Table 9 Trading profits in the VIX futures market

This table presents average abnormal returns (AR) by different net buying pressures. The realized profits are defined as abnormal returns in terms of annualized market-adjusted returns. We long (short) one VIX futures contract at the daily opening price and realize the profits at the daily closing price when the net buying pressure (NBP) in the previous day is higher (lower) than the maximum (minimum) of the past k-day (k=5, 10, and 15) NBPs. The *t*-statistic is reported in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Panel A: Long Strategy

	5-day Maximum	10-day Maximum	15-day Maximum
return	0.1009**	0.0768*	0.0508**
t-statistic	(2.12)	(1.93)	(1.99)

Panel B: Short Strategy

	5-day Minimum	10-day Minimum	15-day Minimum
return	-0.0837*	-0.0598*	-0.0513*
t-statistic	(-1.95)	(-1.75)	(-1.77)

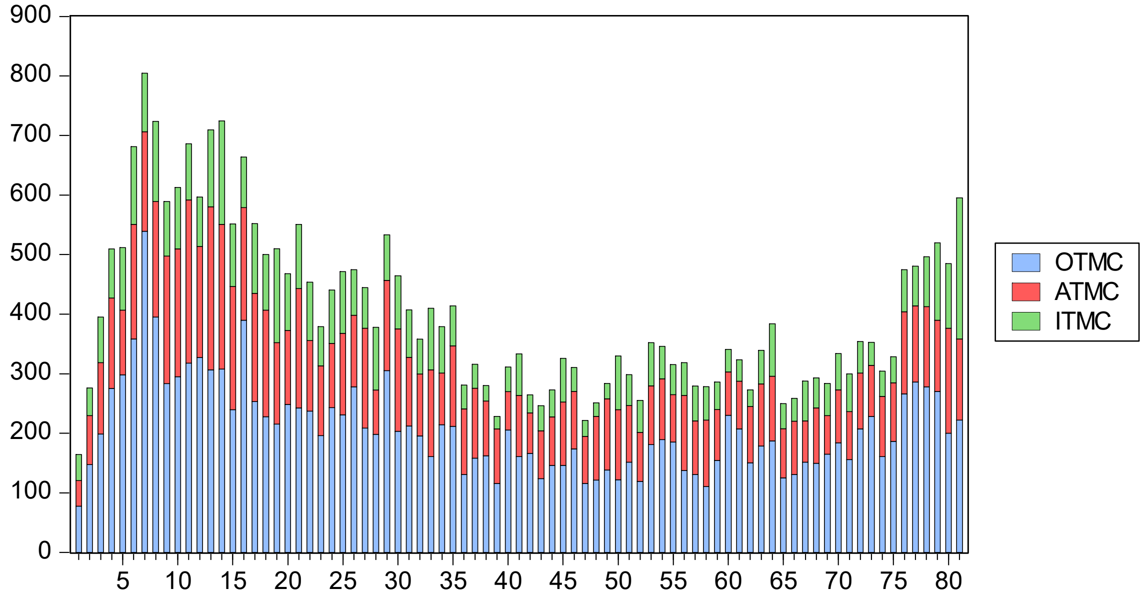

Figure 1a. VIX call volume intraday pattern

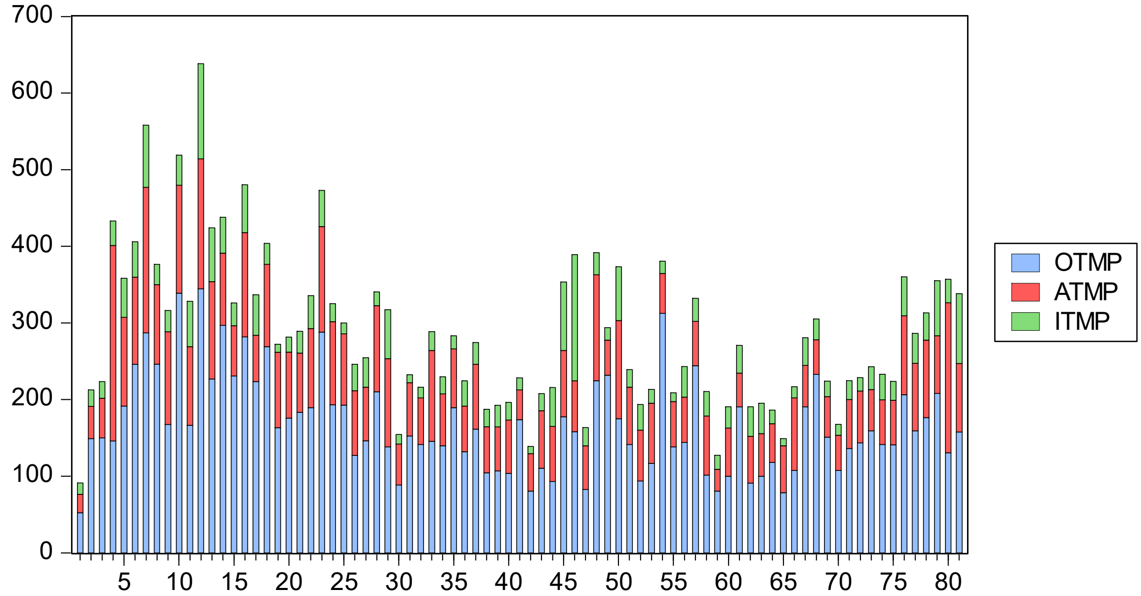

Figure 1b. VIX put volume intraday pattern

Figure 1. Intraday trading activity patterns in VIX calls and puts

Figure 1a (1b) illustrates the intraday patterns of the average number of trading volume for VIX calls (puts); the regular trading hours for both instruments in the CBOE start at 8:30 a.m. and end at 3:15 p.m.; we take the average across 5-minute time intervals each trading day; thus, each day has a total of 81 intervals. The sample period runs from 2 January 2008 to 31 March 2010.