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 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 lowers the next-day delta-hedged option returns. Using several measures proxying for limits to arbitrage, the average levels of the implied volatility curve rise when limits to arbitrage are severe. A trading strategy in the VIX futures market constructed by using the net buying pressure generates an average annualized return of 10.09%.

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ABSTRACT

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 lowers the next-day delta-hedged option returns. Using several measures proxying for limits to arbitrage, the average levels of the implied volatility curve rise when limits to arbitrage are severe. A trading strategy in the VIX futures market constructed by using the net buying pressure generates an average annualized return of 10.09%.

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1. INTRODUCTION

Unlike in a perfectly efficient market, trading activity usually impacts market prices in real world financial markets around the world. For example, market makers may face inventory control problems during periods of large order imbalances, and if the trading amount of buy orders is slightly greater than that of sell orders and exceeds the quantities that they 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 a 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 derivatives markets. Bollen and Whaley (2004) find that option net buying pressure, 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, which is a one-to-one function of market option prices. Gârleanu, Pedersen, and Poteshman (2009) further provide a theoretical model of demand pressure effects in the option market, whereas Muravyev (2016) notes that the price impact of daily order imbalances in option markets attributable to inventory risk is large.

Order imbalance certainly also reflects 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 options markets, such as

Easley, O'Hara and Srinivas (1998), Pan and Poteshman (2006), Kang and Park (2008), 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).

This study aims to provide a comprehensively empirical analysis covering the impact of intraday trading activity of VIX options on their market prices.[1] A closely related paper to this present study is Bollen and Whaley (2004), but our work is different from theirs in several aspects. First of all, we examine the effect of net buying pressure in the newly established and rapidly growing VIX options market. Compared to complex volatility trading strategies in the S&P 500 index options market, VIX options offer investors a simple and direct way to trade volatility without dealing with the other associated risk factors that otherwise affect the overall performance of volatility strategies. Hence, trading VIX options has become a useful risk management tool for investors wanting to hedge their volatility exposure. If there are serious limits to arbitrage in the VIX options market, then investors may face expensive hedging costs for insurance, possibly leading to liquidity spirals such as seen in Brunnermeier and Pedersen (2009). It is therefore worth exploring the extent and sources of trading pressure in the VIX options market. Second, we would like to extend Bollen and Whaley (2004)'s analysis by using intraday data of VIX options so as to have a better understanding of the effect of trading activity on prices.

Our empirical findings show a temporal relationship between the net buying

[1] In related literature, Tsai, Chiu, and Wang (2015) and Kao, Tsai, Wang, and Yen (2018) investigate the informational role of intraday trading activity and quote changes in VIX options with regard to the movements of the VIX index, whereas our study mainly focuses on the trading pressure of VIX options on VIX option price changes.

pressure of VIX options and changes in implied volatility of volatility (IVoV) from VIX option prices. In this case, increased net buying pressure creates positive pressure on option prices, supporting the prediction concerning the limits of the arbitrage hypothesis rather than the information hypothesis. Consistent with the study of Bollen and Whaley (2004), which is associated with limits to arbitrage, the result affects the pricing of VIX options.

We also examine the relationship between the net buying pressure and delta hedge returns in the VIX options market. Our finding shows that the higher net buying pressure of VIX options is associated with lower delta hedge returns of VIX options. These results suggest that the trading amount of buy orders is slightly greater than that of sell orders, resulting in more expensive options with higher option prices and lower delta hedge returns.

Turning our focus to the analyses of limits to arbitrage on VIX option prices, 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 for noise-trader risk (investor attention and sentiment) and funding liquidity (Libor-Tbill and Libor-Repo spreads). Our result documents that the level of the implied volatility curve rises when there are serious limits to arbitrage in the VIX options market.

We further investigate whether intraday prices of VIX futures are affected when liquidity providers face buying or selling pressure in the VIX options market. Hu (2014) also shows that liquidity providers in options hedge their risk exposures in the underlying asset market, leading to changes in the underlying asset price. Thus, we observe the impact of net buying pressure of VIX options on VIX futures returns by building up a trading strategy. The trading strategy in the VIX futures market generates an average annualized risk-adjusted return of 10.09% with a significantly positive *t*-statistic of 2.12, likely implying option trading pressure transmission to VIX futures market via dealers' hedging activity. In other words, our result suggests that VIX futures prices also adjust to order pressure in the VIX options market.

This article contributes to prior research and focuses on high-frequency intraday data to gain a better understanding about the effects of net buying pressure in the VIX options market.[2] In particular, our empirical evidence provides support for the limit to arbitrage hypothesis in the VIX options market. Our results also show that the trading amount of buy orders is slightly greater than that of sell orders, resulting in more expensive options with higher prices and lower delta hedge returns of VIX options. Moreover, our paper investigates the relationship between the proxy variables for measures of the limit to arbitrage and level of the implied volatility curve. Our robust result documents that the level of the implied volatility curve rises when there are serious limits to arbitrage in the VIX options market. Consistent with Hu (2014), our results further support the argument that liquidity providers transfer their exposure from the VIX options market to the VIX futures market through their hedging when large net buying pressure is initiated in the VIX options market.

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

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[2] 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.

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 real world financial markets, arbitraging transactions almost always need capital and can entail various degrees of risk.[3] Furthermore, they also revert asset prices back to their fundamental value and hence eliminate the misplaced price.

Capital constraint is one important reason explaining the presence of limits to arbitrage since the existing literature on limits to arbitrage has widely recognized its importance in financial markets. If arbitrageurs do not have access to additional capital when securities prices diverge, then they may be forced to prematurely liquidate their 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 will prevent arbitrageurs from converging security prices to their fundamental values. In addition, as a change in the composition of the S&P 500 Index, arbitrageurs have a crucial impact on stock prices, resulting in that stocks without close substitutes experience a higher rise in returns; see for example, Wurgler and Zhuravskaya (2002).

A few studies present evidence of the impacts of limit to arbitrage on derivatives prices. For example, Bollen and Whaley (2004) find that order imbalances in options markets affect both the changes in the level and slope of

[3] In fact, as Figlewski (1989) argues, 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.

implied volatility, suggesting that liquidity providers require a premium as compensation 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 in the options market; see for example, Brunnermeier and Pedersen (2009).[4] 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. Muravyev (2016) documents that the 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 are 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 runs in opposite direction to the influences on implied volatility, providing support for the notion of forward-looking information contained in the options market. 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, which is an

[4] 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.

issue yet to be documented within the related literature.

We evaluate two hypotheses through the relationships between changes in implied volatility and net buying imbalance in the VIX options market: (1) the limits to arbitrage hypothesis and (2) the information hypothesis.[5] Following the 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 the limits to arbitrage hypothesis assumes that an 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 the possibility that mark-to-market losses may force liquidation of their positions before convergence.

If each option contract has an upward sloping supply curve, then each implied volatility 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 will be temporary. They revert to the fundamental values as liquidity providers rebalance their inventory positions. On the

[5] This study mainly distinguishes the impacts of intraday trading activity on VIX option prices between information-driven and limits to arbitrage, instead of identifying which types of information. Interested readers can refer to the study of Kang and Park (2008) for more details about information types. Generally, they further propose two information types, including volatility information and direction information, and show that the relationship between net buying pressure and option prices can be accounted for by the information direction in the Korean index options market.

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 will be permanent if net buying pressure contains information.

It is thus beneficial 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 influenced by their 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 ATM (at-the-money) options does not necessarily affect ITM (in-the-money) or OTM (out-of-the-money) option prices. In contrast, under the information hypothesis the net buying pressure for ATM options will generate impacts on changes in other option contracts, since ATM options are usually the most informative about future volatility. In this case, the market prices of all option series will move together in concert with each other.

3. EMPIRICAL METHODOLOGY AND DATA DESCRIPTION

3.1 Data and sample statistics

The underlying asset of VIX derivatives is the VIX index, which is compiled from a portfolio of S&P 500 index options to approximate the expected aggregate volatility of the S&P 500 index during the subsequent 30-calendar-day period. Introduced on March 26, 2004 in the CBOE Futures Exchange (CFE), VIX futures allow market participants to directly act on market volatility. Since then, as a result of the increasing demand for practical market risk management, VIX futures have become a highly successful new product.[6] For example, the average daily trading volume of VIX futures was about 1,864 contracts in 2008, whereas it grew rapidly to about 200,000 contracts by 2014. Subsequently, VIX options began trading on the Chicago Board Options Exchange (CBOE) on February 23, 2006, providing market participants with another tool to manage market volatility. VIX options also present investors with a variety of opportunities to implement their volatility trading strategies or to hedge portfolio volatility risk. The VIX options market is also a rapidly growing market. Taking the annual growth rate of trading volume as an example, VIX options have risen by 166% from 2008 to 2014.[7]

We obtain the VIX derivatives dataset from the CQG Market Data and the CBOE MDR Quotes and Trades Data. The 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 VIX option's contract has positive and non-missing volume data; (iii) we eliminate

[6] Chen and Tsai (2017) examine intraday price discovery competition between VIX and VIX futures and show the dominant role of VIX futures prices in the overall process of price discovery.
[7] The statistics of trading volume were taken from the CBOE official website.

non-positive bid quotes or bid prices that are greater than or equal to the ask prices;[8] (iv) we eliminate data errors, such as trades with zero prices or zero strike prices; (v) the implied volatility of volatility (IVOV) is between 10% and 150%; and (vi) the option matures within 8-90 days.[9] 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 volumes are calculated as each trading volume times trading price.

The trades' executed directions are classified according to the Lee and Ready (1991) algorithm.[10] 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:

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

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

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

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

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

[10] 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).

cumulative distribution function; and T is the time to maturity.[11]

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.[12] The VIX option delta is as follows:

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

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 a bit more often than seller-initiated trades (46.58%).

<Table 1 is inserted about here>

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

[12] 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 options' delta to account for these effects, because the delta is sensitive to underlying volatility and time to maturity.

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; and 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 pressure generally has 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* and *j* represent call or put options contracts in a specified moneyness category, but *i* and *j* cannot be the same options contracts; $\Delta IVoV_t^{moneyness,i}$ refers to the change in the average implied volatility of moneyness VIX call (or put) options in interval *t*; *Ret* denotes the average return of VIX futures; *Vol* is the average dollar trading volume of VIX futures expressed in millions of USD in interval *t*; and $NBP_t^{moneyness,i}$ denotes the net buying pressure of *i* option contracts over an interval t. All variables are calculated across five-minute time intervals.

The above is similar to the setting in Bollen and Whalley (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), $NBP_t^{OTM,i}$ 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 influenced by their 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 between 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 will 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 will be permanent, denoting that these coefficients of lagged change in average implied volatility will be insignificant. The result suggests 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 3 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.[13]

<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:

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

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

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. We carry out the subsequent three regressions using the Newey-West robust correction for standard errors in the coefficients:

$$\Delta IVoV_t^{ATM,i} = \gamma_0 + \gamma_1 Ret_t + \gamma_2 Vol_t + \gamma_3 NBPV_t^{ATM,i} + \gamma_4 NBPV_t^{ATM,j} + \gamma_5 \Delta IVoV_{t-1}^{ATM,i} + \varepsilon_t, \tag{9}$$

$$\Delta IVoV_t^{OTM,i} = \lambda_0 + \lambda_1 Ret_t + \lambda_2 Vol_t + \lambda_3 NBPV_t^{OTM,i} + \lambda_4 NBPV_t^{ATM,j} + \lambda_5 \Delta IVoV_{t-1}^{OTM,i} + \varepsilon_t, \tag{10}$$

$$\Delta IVoV_t^{ITM,i} = \delta_0 + \delta_1 Ret_t + \delta_2 Vol_t + \delta_3 NBPV_t^{ITM,i} + \delta_4 NBPV_t^{ATM,j} + \delta_5 \Delta IVoV_{t-1}^{ITM,i} + \varepsilon_t, \tag{11}$$

where *i* and *j* represent call or put options contracts in a specified moneyness category, but *i* and *j* cannot be the same options contracts; $\Delta IVoV_t^{moneyness,i}$ 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*; $NBPV_t^{moneyness,i}$ denotes the Vega weighted net buying pressure of *i* option contracts over an interval t. All variables are calculated across five-minute time intervals.

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 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.[14] Consequently, we examine whether an 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

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

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.[15] 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 option 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 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

[15] We use the methodology of Clogg, Petkova and Haritou (1995) 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.

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 gradually weakens. 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 effects of net buying pressure on next day delta hedge return in the VIX options market

Given the earlier findings, we further investigate whether investor hedging assets may be forced to be more costly when the limit to arbitrage is severe. Option prices are influenced by demand pressure effects in the options market, suggesting that the price effects may be due to market makers being capital-constrained and unable to perfectly hedge their inventories (Bollen and Whaley, 2004; Garleanu, Pedersen, and Poteshman, 2009). Thus, we seek to examine the impact of net buying pressure on next day delta hedge return in the VIX options market.

We follow Park (2015) and define the delta hedge return that is hedged discretely N times over a period $[t, t+\tau]$, where the hedge is rebalanced at each of the dates t_n, (where we define $t_0 = t, t_n = t+\tau$). The discrete delta-hedged call option gain over the period $[t, t+\tau]$ is:

$$R^{o}_{t,t+\tau,k} = \frac{O_{t+\tau,k} - O_{t,k} - \sum_{n=0}^{N-1} \Delta_{t_n,k} (F_{t_{n+1},k} - F_{t_n,k})}{O_{t,k}} - \frac{r_t^f N}{365} \quad (12)$$

Here, $O_{t+\tau,k}$ denotes the VIX option price at $t+\tau$ day and a moneyness of k; F_{t_n} indicates the VIX futures price; Δ_{t_n} refers to the corresponding option delta; and r_t^f is the risk-free interest rate.

Based on the framework of Christoffersen, Goyenko, Jacobs and Karoui (2018), our analysis includes VIX futures' dollar trading volume, VIX options' average bid-ask spread and average trading volume and controls for the option illiquidity premium, in order to clarify the role of net buying pressure on the relationship between trading activity and option prices. The statistical significance is computed by the Newey and West (1987) robust t-statistics with an optimal lag.

Table 7 shows the impact of net buying pressure on next day delta hedging returns in the VIX options market. The coefficients of net buying pressure are negative and highly statistically significant for both call and put delta hedge returns, regardless of moneyness levels. Our finding shows that the higher net buying pressure of VIX options is associated with lower delta hedge returns of VIX options. These results suggest that the trading amount of buy orders is slightly greater than that of sell orders, resulting in more expensive options with higher option prices and lower delta hedge returns.

Our results are consistent with Christoffersen et al. (2018), who suggest that when market makers set an option price and then price revert at day $t+1$, they are presumably trying to correct some of their earlier net selling at day $t+1$, as a result of negative option delta hedge returns from positive net buying pressure.

<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 VIX options correlates 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 (13), with the intercept being extracted as the level of the implied volatility:

$$\sigma_{k,t}^{imvol} - \sigma_t^{hisvol} = \alpha_{0,t} + \alpha_{1,t}(y_{k,t} - \bar{y}_t) + \varepsilon_{k,t},\ k = 1, 2, ..., n, \tag{13}$$

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 futures 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 respective 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:

$$\alpha_{0,t} = \gamma_{0,t} + \gamma_{1,t} LTA_t^i + \varepsilon_t, \tag{14}$$

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 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 by Search (FEARS) by search proxy for investor sentiment as noise-trader risk. Furthermore, we also use VIX Search to measure noise-trader risk, as defined by the Google search volume index on the key word "VIX". Thus, increased investor attention or sentiment creates positive pressure on prices.

Second, 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 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.

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 providers (such as market makers) gain risk exposures to the underlying price movement and return volatility. Hu (2014) 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 look 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 VIX options' delta as the weight in constructing 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.[16]

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 the 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.[17] The annualized abnormal returns denote the performance of this strategy. We report the average abnormal returns (ARs) by different criteria. Table 9 reports 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 trading intervals. 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 from 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

[16] In our earlier analyses, we calculate net buying pressure for VIX calls and puts, respectively. We estimate overall net VIX futures exposure induced by VIX options to evaluate the impact of net buying pressure in the VIX futures market. The contract multiplier for each VIX futures contract is $1000 and for each VIX options contract is $100. Thus, the net buying pressure is divided by 10.

[17] We use closing price minus opening price of the S&P500 index as our daily price change.

through their hedging when large net buying pressure is 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 volatility (IVOV) from VIX option prices, supporting the prediction concerning the limits of the arbitrage hypothesis rather than the information hypothesis. This result is similar to the argument of Bollen and Whaley (2004) and also documents that the market for VIX options is driven by limits to arbitrage and that investors' net buying pressure in this market does not contain information regarding future prices. We further examine the relationship between net buying pressure and next day delta hedge return in the VIX options market, and our findings still support the limits of the arbitrage hypothesis (Gârleanu et al., 2009; Bollen and Whaley, 2004). Moreover, our paper investigates the relationship between the proxy variables for measures of the limit to arbitrage and level of the implied volatility curve. Our robust result presents that the level of the implied volatility curve rises when there are serious limits to arbitrage in the VIX options market.

Finally, according to the view of Hu (2014), options liquidity providers will, via hedging activities, gain risk exposures to the underlying price movement and return volatility; thus, the underlying asset price change may be induced by delta hedging transactions. We have analyzed VIX future returns around the impact of limits to arbitrage on VIX options prices and follow the set-up strategies due to the net buying pressure of VIX options. Our results further suggest that liquidity providers transfer their exposure from the VIX options market to the VIX futures market through their hedging when large net buying pressure is initiated in the VIX options market.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study have been obtained from two different sources: (a) CQG Market Data; and (b) CBOE MDR Quotes and Trades Data. All data are available on the official websites of these agencies. Restrictions apply as to the availability of the data obtained from these agencies, which were used under license for this study.

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