0DTEs: Trading, Gamma Risk and Volatility Propagation*

Chukwuma Dim† Bjørn Eraker‡ Grigory Vilkov§

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Abstract

We study the recent explosion in trading of same-day expiry (0DTE) options on the S&P500 index. 0DTE positions can destabilize the underlying market when delta-hedging requires trading in the same direction as realized returns. We address this concern by investigating whether measures of trading activity propagate volatility. We find no evidence that aggregate open interest and trading volume increase volatility. On the contrary, market makers' inventory gamma is significantly and negatively associated with future intraday volatility. This evidence is consistent with delta-hedging by market makers because, in our sample, they hold a predominantly positive inventory in 0DTEs.

Keywords: 0DTE, ultra-short options, variance risk premium, volatility trading, gamma risk, volatility propagation

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†**George Washington University**; E-mail: cdim@gwu.edu.

‡**Wisconsin School of Business**; E-mail: bjorn.eraker@wisc.edu.

§**Frankfurt School of Finance & Management**; E-mail: vilkov@vilkov.net.

1 Introduction

Trading volume in short-dated options, especially zero-day-to-expiry (0DTE), has exploded in recent years. For the S&P500 index alone, 0DTEs accounted for 50% of the index options volume in August 2023, up from just 5% in 2016.[1] The major trading hub for equity options, Chicago Board Options Exchange (Cboe), has sequentially increased the number of weekly index option expiration dates to three in 2016 and five in 2022 to eventually have options that expire every day of the week for the next four weeks, thereby facilitating daily 0DTE option trading.

The surge in 0DTE option trading has raised several concerns among market participants and stimulated heated discussions in the press.[2] The primary concern is that large open positions in 0DTEs and other short-term options may induce delta-hedging that can destabilize the underlying market, even when the underlying instruments are very liquid, as is the case for the S&P500 index-based exchange-traded fund (ETF) SPY and S&P500 E-Mini (ES) Futures.[3]

The rationale behind these concerns is that if option sellers delta-hedge, they trade in the direction of the return, i.e., sell additional shares of the underlying during a market decline. The intensity with which hedgers need to re-adjust their positions in the underlying is higher for short-maturity options because these options' delta is more sensitive (measured by "gamma", which is inversely related to option time to expiry) to changes in the underlying. Thus, if market makers hold large short (negative) inventory during the day and systematically delta-hedge it, sudden market moves will be aggravated by their hedging flows. Cboe, observing the largest trading flows in S&P500 0DTEs, disputes such scenarios, claiming that these flows and the resulting market makers' exposure during the day are well-balanced and do not pose a danger. Also, when the intraday open interest gamma of market makers is positive, delta-hedging of inventory

[1] E.g., Volatility Insights: Much Ado About 0DTEs-Evaluating the Market Impact of SPX 0DTE Options.

[2] See, for example, "Surge in zero-day options sparks fears over market volatility," or "Short-term investors in SPY and QQQ warned of options risks."

[3] Average daily trading volume in these markets in 2023 is around 400 bn USD.

generates trades against the direction of return, potentially dampening future volatility. Hu, Kirilova, and Muravyev (2023) show evidence consistent with the hypothesis that option market makers use active inventory rebalancing in addition to delta-hedging to manage risk, indicating that even when market makers hold short option positions, the underlying asset return shocks may not be intensified by 0DTEs.

This paper investigates these contrasting arguments to understand the effects of 0DTE market growth on the stability of underlying markets. We show that 0DTEs now dominate index options markets in terms of trading volume, in line with the extant literature (e.g., Almeida, Freire, and Hizmeri 2023, Bandi, Fusari, and Renò 2023), but are still relatively smaller than longer-term option markets in terms of open interest, directional exposure, and rebalancing risk. We separately analyze the effects of the potential rebalancing needs resulting from high market makers' positions, aggregate market open interest, and high trading volume in 0DTEs and other options with expiry dates of up to a month.

We reconstruct the intraday open interest in short-term options (less than a month to expiry) by trader types and document that market makers' open interest gamma is predominantly positive for 0DTEs. Non-professional customers are, on average, the largest sellers of 0DTEs, while the positions of broker-dealers, professional customers, and firms are relatively small. Crucially, we show that the market makers' intraday open interest gamma for 0DTEs negatively correlates with future realized volatility with a moderate economic magnitude. We can interpret this evidence in two ways: If market makers delta-hedge their, on average, positive inventory, they have a volatility-dampening effect, as they trade in the opposite direction of the market, buying in a down-market and selling during a rally. Consistent with this interpretation, we show that the negative correlation is stronger (by a factor of three) on days of important macroeconomic announcements when uncertainty is greater.

Our evidence is also broadly consistent with a Kyle (1985) information-based story, where market makers absorb information-driven trades by traders with superior volatility forecasting skills. This scenario is possible if market makers charge a sufficiently high bid-ask spread to offset a partially informed order flow. Indeed, the spreads on 0DTE options are very large. For example, on August 1st, 2024, an at-the-money (ATM) SPY call option was trading with a 0.77% bid-ask spread (one penny minimum tick and a price of $1.30), while in 2021-2023, the average effective spread for S&P500 index options near ATM level was 1.5% (Beckmeyer, Branger, and Gayda 2023).

We further analyze how the aggregate dollar gamma of open option positions of different maturities *at market open* shapes the subsequent intraday underlying index realized volatility unconditionally and conditional on past volatility. We use open interest gamma as a proxy for the aggregate market exposure and show that it did not grow after 2016, either for 0DTEs or the other maturities, suggesting that the 0DTEs market growth is unlikely to have exacerbated the effects of potential delta-hedging activity. Indeed, we do not find evidence that the 0DTEs' open interest gamma at market open propagates or unconditionally increases the underlying index volatility. For options with one day to two weeks maturity, open interest gamma is associated with lower realized volatility within the day.

Next, to understand whether 0DTE option trading volume causes high volatility of the underlying index, we analyze the distribution of intraday returns conditional on large jumps in 0DTE volume and find that it is similar to the distribution conditional on moderate and small changes in volume. To study the integration of the underlying and option markets and shock propagation across the markets, we use a structural vector autoregression framework to analyze joint intraday dynamics of the realized variance, trading volume in the 0DTE options, and trading volume in the underlying index instruments.

We find that 0DTEs and underlying markets are rapidly becoming more integrated, with a contemporaneous correlation between intraday trading flows increasing from 0.25-0.30 before 2021 to 0.59 in 2023. Positive shocks to 0DTE trading volume in recent years are associated with and followed by increasingly higher trading volume in the underlying market and vice versa. The observed change in the market structure in recent years also makes the underlying market move stronger with shocks to 0DTE trading volume relative to earlier periods when 0DTE trading was negligible. However, the difference in the magnitude of the average variance response to 0DTE trading across the early and later sample period amounts to only 0.15 standard deviations of the return variance, which is economically negligible. The strength of the volume shock propagation decreases with time to option maturity, with the effects for all options expiring within the next month driven predominantly by 0- and 1DTEs. While we observe a clear time trend in the average intensity of shock correlation (and resulting propagation) between 0DTE and underlying markets, we do not find supportive evidence that sharp intraday jumps in 0DTE trading propagate past market moves and lead to extreme intraday returns.

Our analysis yields some additional insights that are useful for a general understanding of the new and rapidly evolving 0DTEs market. 0DTEs are relatively cheap and do not bear overnight risk. They have extreme leverage close to expiry and demonstrate a very wide distribution of returns. 0DTEs' high leverage and gamma risk make them good candidates for event-based trading. We assess whether these instruments serve this practical purpose in the market by analyzing the intensity of their use for event-based trading compared to longer maturity options around Federal Open Market Committee (FOMC) decision announcements that are known to be associated with the resolution of uncertainty (see, Cieslak, Morse, and Vissing-Jorgensen 2019, Ai, Han, Pan, and Xu 2022). We show that traders use ultra-short-term options, mainly 0- and

1DTEs, to bet on the resolution of uncertainty.[4] Compared to the longer maturity options, the trading volume in the zero- and one-day-to-expiry options significantly declines in the half-hour interval before FOMC announcements and rebounds significantly after the announcement.

In recent years, investors have been increasingly selling volatility for yield-enhancing (e.g., Todorov and Vilkov 2024), resulting in net option buying by delta-hedgers. Moreover, anecdotal evidence on the popularity of particular option strategies suggests that retail customers also actively sell volatility using 0DTEs, while market makers, the most active delta hedgers, are net buyers with positive open interest gamma.[5] Accordingly, the market makers' positioning in our sample period results in their delta-hedging trades having a significant dampening effect on the underlying volatility instead of the amplification feared by several market participants. Although the pattern suggests no cause for alarm, it is important to note that if market dynamics, regulation, and risk management practices were to encourage market makers to change their strategy and build up a large negative gamma inventory in 0DTEs, their delta-hedging flows can indeed intensify overnight and intraday market jumps, propagating directional moves.

We contribute to several strands of research. A quickly increasing number of papers study the patterns in 0DTE options trading (e.g., Beckmeyer, Branger, and Gayda 2023), work on specially designed pricing models for short-term options (e.g., Bandi, Fusari, and Renò 2023), and document stylized asset pricing facts related to 0DTEs and other ultra short-term options (e.g., Almeida, Freire, and Hizmeri 2023, Vilkov 2023, Johannes, Kaeck, Seeger, and Shah 2024). Brogaard, Han, and Won (2023) examine the impact of 0DTEs trading on intraday volatility and find that 0DTEs' relative turnover is positively related to the intraday volatility of the underlying. In contrast, our study has a different focus and design. We analyze (i) the rebalancing risks of market makers' and aggregate open positions in 0DTEs vs. longer-maturity options and

[4]Johannes, Kaeck, Seeger, and Shah (2024) show similar results for 1DTEs. Londono and Samadi (2024) also use the daily expiration S&P500 index options to document a much larger variance risk premium for options that span key economic data releases than those that do not.

[5]See, for example, 0DTE Options Strategies: Insights from 25k Trades.

their *conditional* impacts in propagating past realized volatility onto future intraday volatility, and (ii) the *conditional* intensity of intraday shock propagation between index returns and trading volumes in 0DTEs and underlying markets.[6] A follow-up paper by Adams, Fontaine, and Ornthanalai (2024) uses the introduction of 0DTE expiration days to confirm that underlying volatility decreases on days with 0DTEs. To the best of our knowledge, our paper is the first to systematically study the effects of gamma exposures in 0DTEs on the underlying variance.

We also relate to the empirical literature on the impact of option trading and open interest on the underlying. Ni, Pearson, Poteshman, and White (2021) analyze absolute returns and lagged net gammas for firms and market makers. They suggest higher inventory leads to lower volatility when inventory is positive, but negative inventory predicts higher future volatility. Our analysis offers important additional insights because the delta hedging of 0DTE positions have a larger potential for destabilization due to more frequent and larger rebalancing than for longer-term options. Baltussen, Da, Lammers, and Martens (2021) show that past intraday returns predict the last half trading hour returns for various assets. For SPX, the latter is not significantly related to net gamma but is negatively and significantly related to the interaction of net gamma and lagged return. Barbon and Buraschi (2020) study intraday momentum and show that autocorrelations are significantly related to the difference between call and put options' gamma. J.P.Morgan (2023) reports a stronger intraday mean reversion of returns due to 0DTE flows. Anderegg, Ulmann, and Sornette (2022) suggest that exchange rate volatility significantly increases with the aggregate option gamma, such that delta hedgers' order flow leads to a 0.7% (0.9%) increase in EUR/USD (USD/JPY) annualized volatility. Sornette, Ulmann, and Wehrli (2022) study Gamestop's stock price in Spring 2021, noting that as the stock price rose, call option sellers were forced to buy, leading to a price spiral. Lipson, Tomio, and Zhang (2023)

[6] We compare our results and reconcile some of the differences in our approaches in Section 5.

show that shocks to retail option trading due to Robinhood's introduction of options increased optionable stocks' return volatility.

Our paper also relates to theoretical works (e.g., Jarrow 1994, Frey and Stremme 1997, Frey 1998, Platen and Schweizer 1998) that analyze how options trading and hedging affect the price of the underlying. This literature notes that the hedging demand equals the Black-Scholes net position gamma scaled by time-to-maturity and the options trader's perceived volatility. Thus, total hedging demand is proportional to the position size by option hedgers, and if option hedgers trade a sufficiently large volume, the stock price volatility explodes as an upward or downward price spiral ensues. We analyze how the potential hedging demand for ultra-short-term options relates to the underlying volatility and how the former is differentially reflected in the pricing of short- and longer-maturity options.

We also add to a well-developed literature on index options returns and variance risk premiums (e.g., Carr and Wu 2009, Bollerslev, Tauchen, and Zhou 2009, Dew-Becker, Giglio, Le, and Rodriguez 2017, Aït-Sahalia, Karaman, and Mancini 2020, Eraker and Wu 2017). We complement these studies by documenting new facts about realized variance risk premiums on the shorter range of maturity spectrum up to 30 days, especially ultra-short-term options expiring within hours instead of days. We show that the magnitude of VRP goes up sharply towards expiry. To our knowledge, our paper is the first to document the negative association between 0DTE open interest gamma and the intraday realized variance risk premium.

The remainder of the paper is organized as follows. Section 2 discusses the data and definition of risk, return, and trading activity variables. Section 3 presents empirical results that compare aggregate market activity, risks, and returns in 0DTEs to longer maturities. Section 4 analyzes the propagation of volatility by 0DTEs and longer-maturity options' open interest gammas and looks at the interplay between intraday volatility and trading activity in 0DTEs and underlying markets. Section 5 presents robustness tests and additional analysis, and Section 6 concludes.

2 Data and Variables Preparation

This section summarizes data sources and processing rules in Section 2.1 and variable construction in Section 2.2.

2.1 Data Sources

Options. We work with options data for the S&P500 index (ticker SPX) and the SPDR S&P 500 ETF Trust (ticker SPY). Options on the index are of European type and cash-settled against the close (16:00 Eastern Time, ET) of the S&P500 market index. SPY options have American exercise and are settled physically on the evening of the expiration date. The regular trading session starts at 9:30 ET, though the options are also traded in the extended trading session before and after the regular session. The S&P500 index has several option roots due to differential settlements: SPX has its expiration at the open (AM) of the third Friday of each month, and SPXW has the (PM) expiration at 16:00 ET, once per week before August 2016, then three times per week, and then adding sequentially one extra day on April 18, 2022, and May 11, 2022. SPY also had options with three weekly expiration dates for several years and now has the same expiration schedule as SPXW. Currently, Cboe offers options on the S&P500 index and SPY with expiration each day for the next month and some longer maturities. All the considered options have a multiplier $m = 100$, i.e., the notional of one option contract is given by 100 times the underlying price. As the SPY trades at roughly 1/10th of the SPX, the nominal size of one SPX option contract is roughly ten times that of an SPY contract. For the analysis, we use options with roots SPXW and SPY.

We use three source data formats for the options: intraday bars, intraday Cboe open-close volume summary, and actual transactions. 30-minute intraday bars from Cboe DataShop are available from 2012 to 6/2023 and include national best bid and offer (NBBO) with size, open/high/low/close (OHLC) prices and trade volumes, price of the underlying instrument, open interest at the beginning of each day, implied volatilities and selected sensitivities (i.e., Greeks, including delta and gamma).[7] Open-close volume summary data at 10-minute frequency are available from 2021 to 6/2023 for the C1 platform and provide trading volumes for all available option contracts traded on C1, split into aggregate buying and selling flows classified by origin (i.e., trader types including market makers, customers, pro-customers, firms and broker-dealers).[8] Transactions data from Cboe DataShop are available from 2012 to 6/2023 and represent enhanced data from the Options Price Reporting Authority. It includes trade price and size, the exchange where the trade printed, the NBBO quote and size, the underlying bid-ask, and the implied volatility and the calculated delta of the trade. This data are not cleaned by the provider, and we parse it using filters and procedures similar to Bryzgalova, Pavlova, and Sikorskaya (2023).[9] After the initial parsing, we first aggregate simultaneous trades with the same conditions and then aggregate the data to the 1-minute bars by adding up trade volumes for each 1-minute bar and group, comprised of the expiration date, option type, and strike.

We restrict the sample to options on the S&P500 index with the regular (PM) expiration (roots SPXW and SPY), expiring within the next 30 calendar days. We compute for each option on each day its days-to-expiration (DTE), counting only working days (so that an option observed on Friday and expiring on Monday is 1DTE). We compute various market statistics for the options up to 22DTEs and then concentrate in more detail on options with extremely short maturities (0- and 1DTEs).

[7]On seven dates (24, 26/10, 14/11, and 10, 12, 19, 24/12 of 2018) due to data issues we have zero open interest reported, and we exclude these dates from the analysis.

[8]Note that all the SPX/SPXW options trading takes place on C1, while SPY options are also traded on other platforms. To reconstruct open interest by trader types one needs to observe all open and close transactions; hence, we exclude SPY root from the analysis of intraday open interest based on the open-close volume data.

[9]We appreciate having access to the paper replication package at https://tinyurl.com/reppackage, and port the original R code to Python with slight adjustments. We keep the trades with zero `canceled_trade_condition_id`, positive `trade_size` and `trade_price`, non-negative bid-ask spread `spread`, `underlying_bid` weakly larger than 0.01 (vs. 0.1 in Bryzgalova et al.), and `trade_price` between `best_bid - spread` and `best_ask + spread`.

Underlying Markets. We obtain the end-of-the-day (EOD) closing prices and 1-minute OHLC (open, high, low, close) price bars for SPX, and OHLC with traded volume bars for SPY and the continuous front contract of the S&P500 Mini-futures (ES) from *DTN IQFeed*.[10]

2.2 Construction of Main Variables

Realized Variances and Intraday Return Distributions. We use EOD closing prices of SPX and SPY at 16:00 to compute the final payoff for the available options (we assume that payoff on options with physical exercise can be approximated by the cash settlement at the day close) according to its type. We also compute intraday returns for different time intervals by aggregating 1-minute realized SPX returns.

We compute realized variances (RV) for intraday time intervals from a given point in time t_0 to a subsequent point t_1 on the same day d as a sum of squared 1-minute log returns:

$$RV_{t_0,t_1} = \sum_{t=t_0}^{t_1-1} r_{t,t+1}^2, \tag{1}$$

where $r_{t,t+1}$ is SPX log return for the minute ending at $t+1$ computed as close to close from t=9:31 until T=16:00 on the same day. For longer periods (e.g., from a time point today to an expiration time in several days) we adapt the methodology of Hansen and Lunde (2005), and compute the realized variance as the sum of variance from a given bar until the end of the day $RV_{t_0,T}$ and a weighted sum of overnight and intraday variances for the following full days until expiration of an option with dte trading days to expiry:

$$RV_{dte,t} = RV_{t,T} + \omega_1 RV_{dte}^{on} + \omega_2 RV_{dte}^{day}, \tag{2}$$

[10] In the first half of 2023, daily trading volumes in SPY and ES front contract were around 100 million shares and 1.5-2 million contracts per day, respectively. Futures have a notional of 50 units of the index, and SPY is approximately 1/10 of the index; hence, turnover in SPY and ES corresponds to 10 and 75-100 million units of the index, respectively. Thus, SPY is approximately ten times less liquid than ES, and the latter has the advantage of overnight trading sessions. Anecdotal evidence suggests that delta-hedging of index options happens in both markets, but Minis are preferred by large traders.

where RV^{on}_{dte} is the sum of squared overnight log returns from the close of day d until expiration corresponding to dte, and RV^{day}_{dte} is the sum of intraday log returns from day $d+1$ until expiration corresponding to dte.[11] The weights ω_k are determined for each day d following Hansen and Lunde (2005) using an annual rolling window of 251 daily log returns until $d-1$. We compute overnight returns from close at 16:00 on the previous day to open at 9:31 in the morning.

Trading Activity and Risk Variables. To analyze the dynamics of market activity and aggregate risks in the option markets, we quantify open interest as both aggregate start-of-day (SOD) open interest reported by the Options Clearing Corporation and intraday open interest by origin (trader types) computed from the Cboe open-close volume summary data at 10-minute frequency, and trading volume computed from both 30-minute bar data or actual transactions (for higher frequency). Volumes and open interest are converted from number of contracts to dollar terms, either dollar notional or dollar sensitivity (option Greeks).

Start-of-day d open interest $OI_{d:sod,C}$ for a contract C (combination of underlying instrument j, option type $cp \in \{C(all), P(ut)\}$, trading days to expiry dte) is in terms of number of open contracts. We express it in terms of dollar notional, dollar delta and dollar gamma:

$$\begin{aligned} OI^{\$}_{d:sod,C} &= OI_{d:sod,C} \times 100 \times S_{j,d:sod} \\ OI^{\$\Delta}_{d:sod,C} &= OI_{d:sod,C} \times 100 \times \Delta_{d:sod,C} \times S_{j,d:sod} \\ OI^{\$\Gamma}_{d:sod,C} &= OI_{d:sod,C} \times 100 \times \Gamma_{d:sod,C} \times S^2_{j,d:sod}, \end{aligned} \tag{3}$$

where $S_{j,d:sod}$, $\Delta_{d:sod,C}$, and $\Gamma_{d:sod,C}$ are the price of underlying j, delta, and gamma of the option contract C with underlying j, all measured at the close of the first available bar in our data (i.e., 10:00 ET) of day d. Multiplier 100 adjusts for the notional of an option contract.

[11] We include the first minute of the day in overnight return to let markets open for most stocks and absorb the accumulated demand and supply from the pre-open period.

Intraday open interest by trader types (firm, broker-dealer, market maker, customer, and pro-customer) is computed from open-close volume summary. The data contain (at 10-minute frequency within each day) the cumulative (from the day start) trading volumes for each contract, split into buy and sell flows for market makers and buy open, buy close, sell open and sell close flows for the other trader types. For each contract C and trader type TT, at the end of each 10-minute bar $d:t$ on day d, we compute cumulative order imbalance from the start of a day:

$$CDOI_{d:0\to t,TT,C} = \begin{cases} \text{market maker:} & Buy_{d:0\to t,TT} - Sell_{d:0\to t,TT,C} \\ \text{other } TT\text{:} & BuyOpen_{d:0\to t,TT,C} + BuyClose_{d:0\to t,TT,C} \\ & - SellOpen_{d:0\to t,TT,C} - SellClose_{d:0\to t,TT,C}, \end{cases} \tag{4}$$

and convert it to the 10-minute daily order imbalance by calculating the first difference of the data points within each day: $DOI_{d:t,TT,C} = CDOI_{d:0\to t,TT,C} - CDOI_{d:0\to t-1,TT,C}$, setting $DOI_{d:0,TT,C} = CDOI_{d:0\to 0,TT,C}$ to account for pre-market trading. By default, the order imbalance of the market makers is equal to minus aggregate order imbalance of other trader types, i.e., market makers absorb the net demand and supply from other market participants managing their inventory of option contracts. To get the open interest $OI_{TT,d:t,C}$ held by trader type TT in a given contract C at date-time $d:t$, we accumulate the 10-minute order imbalances $DOI_{d:t,TT,C}$ from up to 180 days before the expiration of the contract C until $d:t$.[12] We compute open interest $OI_{TT,d:t,C}$ at the end of the 30-minute time intervals within each day to match our 30-minute bars with prices and Greeks, and then we convert it to dollar notional, delta and gamma terms following the procedure for start-of-day open interest in (3), but using underlying prices and Greeks for the matching time points.

Volume for a given contract C and a particular time interval $d:t_0 \to t_1$ on day d (typically, one- or 30-minute bar) is also specified in number of contracts, and we convert it to absolute

[12] We implicitly assume that market makers hold a negligible open interest in long-term option contracts. Changing the window to 30 days does not materially impact our results.

dollar delta terms using delta value and stock price at the end of the interval:

$$Vol^{\$\Delta}_{d:t_0\to t_1,C} = Vol_{d:t_0\to t_1,C} \times 100 \times |\Delta_{d:t_1,C}| \times S_{j,d:t_1}, \tag{5}$$

For the analysis of the start-of-day open interest and aggregate volume, we sum the per-contract variables over a set of all contracts for options with roots SPXW and SPY, i.e., index and ETF weeklys, over expiration buckets (0DTE, 1DTE, 3-5DTE, 6-10DTE, and 11-22DTE), as a snapshot for a given time point or an average value over a period, or a combination of both. For the analysis of the intraday open interest by trader types, we use only SPXW contracts, which are traded exclusively on the C1 platform and for which we can "reconstruct" the open interest.

3 Market Dynamics: 0DTE and Longer-term Options

This section analyzes in Section 3.1 the dynamics of trading volumes and aggregate risks for options of various maturities. Section 3.2 documents the intraday dynamics of open interest and rebalancing risks by trader types.

3.1 Trading Volumes and Aggregate Risks

We examine the overall market statistics for options maturing in the next 22 trading days (i.e., one calendar month), concentrating on the differences across maturities and splitting DTEs into 0, 1, 2-5, 6-10, and 11-22 trading days to expiration buckets to clearly separate very short-term options from longer-term ones.

To analyze market composition and dynamics, we aggregate the open interest and volume variables on each day d by integrating out option type and time of the day for a given strike range from the open interest and dollar volume equations (3) and (5). For open interest variables on day d, we add up observations at the end of the first bar (i.e., 10:00) for all call and put

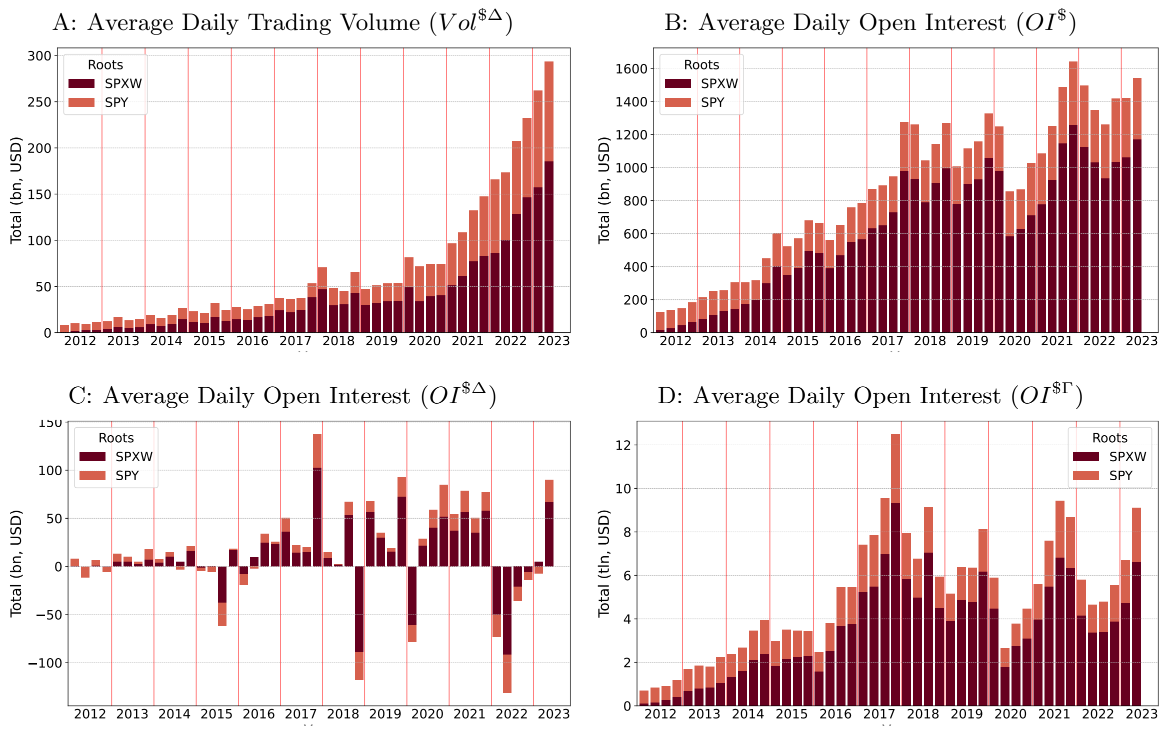

Figure 1: Aggregate Market Statistics. The figure shows quarterly averages of daily volume and open interest variables for SPXW and SPY options expiring within the next 22 trading days. We aggregate variables in equations (3) and (5) on each day by summing over contracts up to 22 DTEs and moneyness in $[0.5, 1.5]$ the start-of-day open interest variables and sum of intraday volume variables for all available bars, and compute quarterly averages. The sample period is from 01/2012 to 14/06/2023.

options with moneyness $K \in [0.5, 1.5]$. For volume, we sum all observations of all options in the selected moneyness range during the day. To compute the open interest and volume variables for DTE buckets, we sum aggregate variables over the required dte range on each day$d$.

Figure 1 gives the first impression of the market development over the last decade, by aggregating volume and open interest variables for SPX weekly and SPY options with maturities within the next 22 trading days. SPY options are popular among individual investors due to the low notional value of the contract. Accordingly, the average trading volume in Panel A for SPY is relatively high—about 40-45% of trading in index options. At the same time, Panels B to D demonstrate that aggregate risks are predominantly held in the index options: open interest in terms of dollar notional, delta and gamma for SPX is about four times higher than for the

SPY. It indirectly suggests a more speculative and retail character of SPY options, though, for a formal claim, one needs to analyze volume and open interest composition in detail.

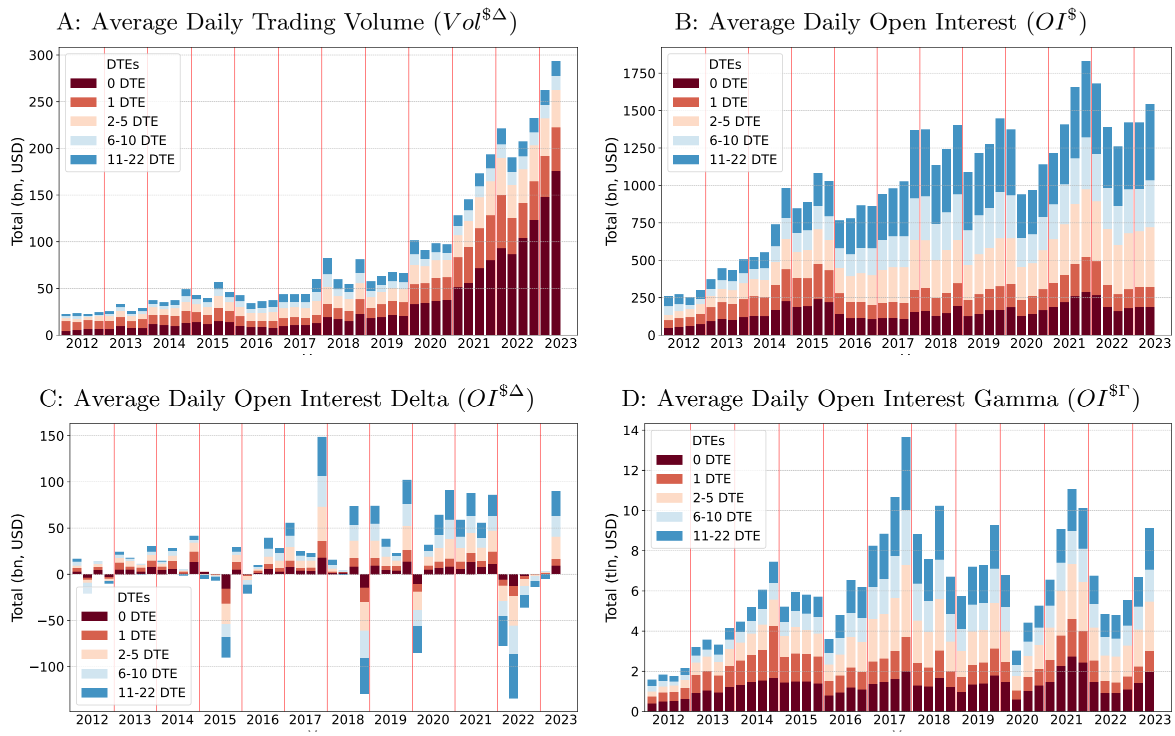

Figure 2: Market Statistics by Days to Expiration. The figure shows quarterly averages of daily volume and open interest variables for SPXW and SPY options by expiry buckets (0, 1, 2-5, 6-10, 11-22 DTEs). We aggregate variables in equations (3) and (5) on each day by summing over all contracts with moneyness in $[0.5, 1.5]$ and pre-defined DTE buckets the start-of-day open interest variables and sum of intraday volume variables for all available bars, and compute quarterly averages. The sample period is from 01/2012 to 14/06/2023.

Figure 2 provides a split of average volume and open interest measures by DTE buckets and delivers two messages: First, average daily trading volume growth is mainly due to the 0DTEs, for which the depicted evolution of trading volume resembles a quadratic function. Second, the open interest dollar delta (i.e., directional risk) in Panel C due to 0DTEs is an order of magnitude smaller than for longer-term options and has not increased over time. The open interest in terms of dollar notional and dollar gamma has been relatively stable over the years and is comparable across DTE buckets. The pattern fits well with the intuition that the direction of daily risk in extremely short-term options often changes such that, on average, the dollar deltas net out. On the other hand, flipping (often) the delta of a longer-term option portfolio is costly, and its sign generally corresponds to longer-term market sentiment in a given quarter. 0DTEs' open interest and dollar gamma are nevertheless high, indicating a non-trivial size of daily directional bets and resulting gamma risk on the market. Interestingly, introducing two extra weekly expiration dates in August 2016 and two more in April-May 2022 does not seem to have a pronounced effect on any of the quantities. The trading volume witnessed a relatively sharp increase only in 2020, but because it happened in the first quarter of the year, possibly linked to at-home COVID-related trading by individual investors.

	Count	Mean	StDev	Min	25%	50%	75%	Max
Full Sample Period								
Trade Volume (USD, bn)	1447	192.7	204.7	4.1	40.4	89.7	304.5	854.4
Trade Volume Delta (USD, bn)	1447	47.0	49.5	1.3	11.9	23.4	71.4	227.1
Open Interest (USD, bn)	1447	163.6	113.4	11.3	78.7	132.8	216.8	849.3
Open Interest Delta (USD, bn)	1447	3.2	19.1	-135.4	-3.8	2.9	11.3	118.8
Open Interest Gamma (USD, bn)	1447	1376.0	906.4	7.0	712.6	1170.9	1773.5	7245.7
Before 09/2016								
Trade Volume (USD, bn)	287	30.0	17.5	4.1	15.3	26.6	41.6	87.9
Trade Volume Delta (USD, bn)	287	9.6	5.4	1.3	5.3	8.5	12.9	26.2
Open Interest (USD, bn)	287	134.7	77.9	11.3	74.6	124.3	188.5	375.0
Open Interest Delta (USD, bn)	287	2.6	14.2	-44.1	-3.3	1.7	10.6	43.9
Open Interest Gamma (USD, bn)	287	1117.1	625.4	7.0	555.1	1095.3	1558.2	3855.7
From 09/2016 to 04/2022								
Trade Volume (USD, bn)	878	133.6	113.5	8.8	50.0	91.0	193.7	537.1
Trade Volume Delta (USD, bn)	878	33.0	26.9	2.0	13.8	23.3	45.4	132.5
Open Interest (USD, bn)	878	168.2	118.3	17.8	75.4	129.1	236.4	849.3
Open Interest Delta (USD, bn)	878	4.6	20.0	-135.4	-2.8	3.8	12.2	118.8
Open Interest Gamma (USD, bn)	878	1502.0	994.8	131.3	765.3	1226.6	2015.0	7245.7
After 04/2022								
Trade Volume (USD, bn)	282	542.0	121.5	227.6	466.4	539.8	626.3	854.4
Trade Volume Delta (USD, bn)	282	128.8	39.8	39.7	101.3	128.8	155.3	227.1
Open Interest (USD, bn)	282	178.7	123.1	41.1	104.1	142.1	183.9	720.7
Open Interest Delta (USD, bn)	282	-0.4	20.4	-106.8	-7.0	0.6	8.2	72.7
Open Interest Gamma (USD, bn)	282	1247.5	779.1	157.5	699.8	1108.3	1608.4	5944.2

Table 1: 0DTEs Volume and Aggregate Open Interest. The table provides average start-of-day open interest and volume defined in equations (3) and (5) for options with roots SPY and SPXW and zero days to expiry (0DTEs). The variables are aggregated for each day: for open interest as the sum of the respective start-of-day open interest variables for all contracts, and for volume as the sum of volumes for all contracts for all 30-minute bars during the regular session from 9:30 to 16:00. The sample period is from 01/2012 to 14/06/2023.

Table 1 provides more detailed summary statistics of 0DTEs volume and aggregate SOD open interest variables. The summary statistics are shown for the whole sample period, the sub-period with only one expiration per week (before 09/2016), the sub-period with three expiration dates per week (from 09/2016 to 04/2022), and the sub-period with expiration each day (after 04/2022). Turnover in the 0DTEs has increased substantially during our sample period, and according to the *Min* column, 0DTEs demonstrate very good daily liquidity in recent years. Average open interest deltas are close to zero, with plenty of time-series variation, indicating that 0DTEs are actively used in betting on direction. Aggregate dollar gammas are relatively stable over time (1 to 1.5 tln) but demonstrate a pronounced right tail with maximum values of 6-7 tln per day, which is more than six sigmas (StDev) from the mean.

Overall, we do not observe any increase in the open interest of 0DTEs following the exponential growth in their trading volumes. Since the open interest, not the volume, mainly affects the rebalancing risks of option positions, the observed statistics suggest that it is unlikely that additional sizeable risks stem from 0DTE market growth. Table A1 in the Appendix provides additional summary statistics for options in the other DTE buckets, with an important message: while turnover in the longer-term options has increased far less dramatically than for 0DTEs, at least for options up to a week to expiration, the total directional bets (deltas) and potential gamma risk are similar if not larger compared to options expiring today.

3.2 Trading Activity by Trader Types

Market makers are typically considered the trader type that delta-hedge their positions, at least partially (see, Hu 2014, Ni, Pearson, Poteshman, and White 2021). Furthermore, market makers face trading flows from other market participants, and they manage their inventory to keep risks under certain limits. Thus, we are especially interested in the activities and exposures of market makers when analyzing the decomposition of open interest by trader types.

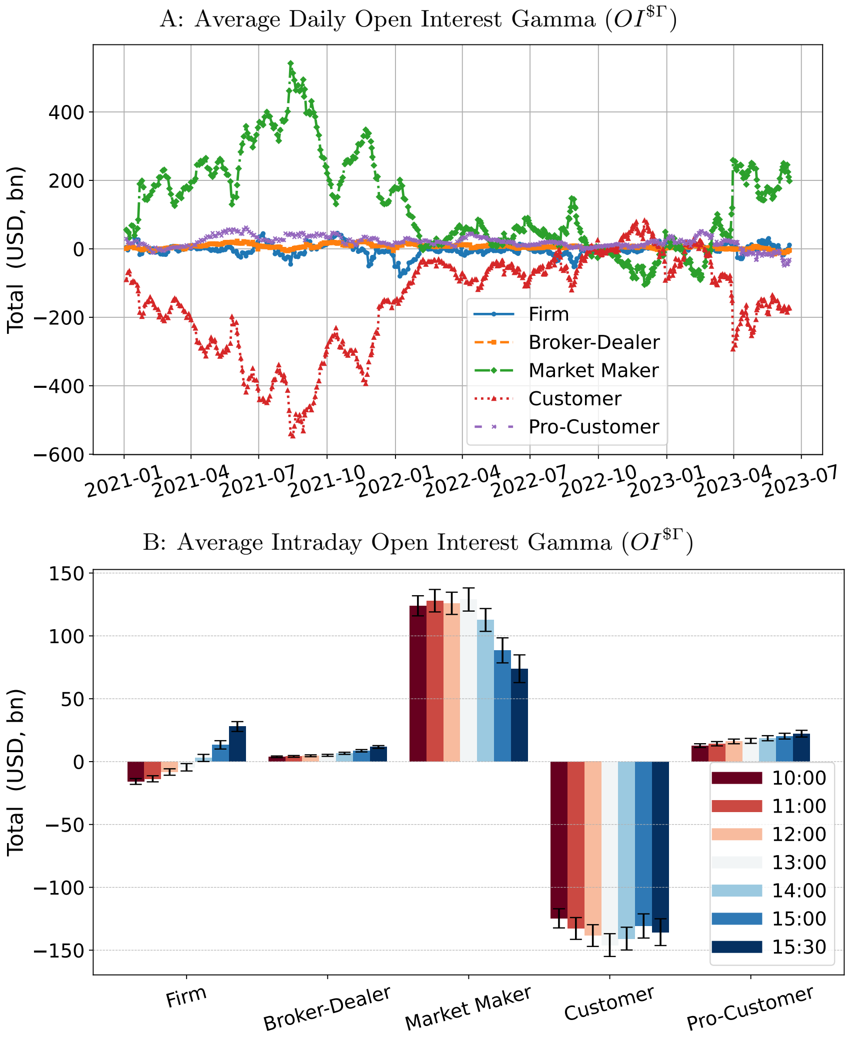

Figure 3: 0DTE Open Interest Gamma by Trader Types. The figure shows the time series of the average intraday 0DTE open interest dollar gamma $OI^{\$\Gamma}$ by trader types (Panel A) and the average intraday 0DTE open interest dollar gamma $OI^{\$\Gamma}$ by points in time and trader types and their 95% confidence bounds (Panel B). Open interest gammas are computed for 0DTE SPXW options. Series in Panel A are smoothed using an exponential moving average with a half-life of five days. The sample period is from 01/2021 to 14/06/2023.

Figure 3 shows the time series of the open interest dollar gamma in Panel A and the average intraday open interest dollar gamma at different points during the day in Panel B, both split by trader types. Surprisingly, market makers' open interest gamma is, on average, positive and remains positive for most of the sample period (during our sample period, only about one-third of observations have a negative open interest gamma, with an average magnitude of roughly three times smaller than that of the positive gamma). This picture indicates that market makers predominantly hold long options positions. The major sellers are non-professional customers, while firms, broker-dealers, and pro-customers hold far smaller exposures on average. During the day, market makers' exposure is positive on average and decreases monotonically, while customers hold roughly constant dollar gamma exposure, and that of the other trader types increases slightly.

Importantly, we do not observe any positive correlation between the rapidly increasing trading volumes in 0DTEs and the market makers' open interest dollar gamma in the morning or throughout the day. Figure A1 in the Appendix provides additional figures for options in the other DTE buckets, which confirm that at least in the considered period, market makers are also long gamma in other maturity buckets considered in our analysis, with customers being on the other side of the open interest.

4 0DTE Trading as a Risk Factor

4.1 Variance Propagation Through Gamma Risk

We now turn to how the market makers' intraday open interest gamma relates to the future intraday realized variance, thereby shedding light on the impact of 0DTEs market dynamics on the underlying market.

4.1.1 Intraday Open Interest and Variance

A direct causal mechanism through which 0DTEs market dynamics can affect the underlying variance is the market makers' delta-hedging activity. To set the stage for the subsequent analysis that tests this causal channel, we provide an illustration of the mechanism, building on earlier works focused on long maturity options (e.g., Ni, Pearson, Poteshman, and White 2021).

Assume that the underlying index S_t follows a diffusion process with constant volatility so that an option's delta $\Delta_t = \frac{\partial V}{\partial S}|_{S=S_t}$ is a function of stock price and time to expiry $\Delta_t =$

$f(S_t, T-t)$. The Greeks are linear operators, so the portfolio delta is just a sum of deltas of options in the portfolio, and we assume aggregate delta right away. To quantify the rebalancing required to maintain a delta-hedged position (ignoring the direct rebalancing of option positions), we use Ito's Lemma to get the differential change of the portfolio delta:

$$d\Delta = \frac{\partial \Delta}{\partial S} dS + 0.5 \frac{\partial^2 \Delta}{\partial S^2} (dS)^2 + \frac{\partial \Delta}{\partial t} dt = S\Gamma \frac{dS}{S} + 0.5 S^2 \frac{\partial^2 \Delta}{\partial S^2} \left(\frac{dS}{S} \right)^2 + \frac{\partial \Delta}{\partial t} dt,$$

so that the change in delta after underlying realized return r_{t_0,t_1} from t_0 to t_1, in terms of the number of units of underlying, is approximately equal to

$$\Delta_{t_1} - \Delta_{t_0} \approx S \times \Gamma \times r_{t_0,t_1} + 0.5 S^2 \times \frac{\partial^2 \Delta}{\partial S^2} \times r_{t_0,t_1}^2 + \frac{\partial \Delta}{\partial t}(t_1 - t_0), \tag{6}$$

where the first term quantifies the direct gamma effect, the second term quantifies the effect of gamma change, called "speed," and the third term quantifies delta time-decay, called "charm." For small time intervals it is customary to neglect second-order and time effects, and we also concentrate on the gamma effect in the main analysis.[13] In dollar terms, the excess portfolio delta to be offset through rebalancing can be approximated as follows:

$$\widehat{\$\Delta}_{t_1} \approx S^2 \times \Gamma \times r_{t_0,t_1} = \$\Gamma \times r_{t_0,t_1}. \tag{7}$$

This expression tells us that a delta-hedger with a positive options portfolio gamma will sell the underlying asset after positive returns and buy it after negative returns, dampening the subsequent volatility. Delta-hedgers with negative gamma will do the opposite, propagating large jumps and thus increasing volatility. In such a scenario, we would observe a negative link between the current level of the delta-hedger's open interest gamma and future volatility. On the other hand, we would observe no significant association between current open interest gamma

[13] In the Robustness and Extensions Section 5 we also discuss the effect of speed and charm, and show that including higher-order effects does not affect our conclusion.

and future volatility if (i) all traders on both sides of open interest delta-hedge and their trades offset each other, (ii) delta-hedgers maintain gamma levels close to zero and the rebalancing flows are small compared to the underlying market liquidity, and (iii) no traders delta-hedge but instead rebalance their option positions directly. A positive association between open interest gamma of a group of traders and future volatility could arise if these traders are better-informed and adjust their inventory in anticipation of future volatility.

Delta-hedging can be very expensive, especially in 0DTEs, because their gamma and the required intensity of rebalancing are increasing sharply on the expiry day. Following Ni et al.(2021), we hypothesize that market makers are the major group of large traders realistically able to delta hedge 0DTEs. At the same time, we also know from Hu, Kirilova, and Muravyev (2023) that market makers could use active inventory rebalancing instead of delta-hedging to manage risk, and in case of short-term options they may be even more inclined to do so.[14]

To empirically assess whether the intraday patterns of market makers' inventory in short-term options and subsequent volatility are consistent with any of the outlined scenarios, we regress the 30-minute realized log-variance following every 30-minute intraday interval between 11:00 (so that the intraday lagged variables belong to the same day) and 15:30 on the levels of market makers' dollar gamma observed at the end of such intervals:[15]

$$\ln RV_{t+1} = b_0 + \sum_n b_{nDTE} OI^{\$\Gamma}_{MM,t,nDTE} + \mathbf{CX} + \varepsilon_z, \tag{8}$$

where $\mathbf{X}$ is a vector of controls including three lags of dependent variable and three lags of realized 30-minute returns, and time dummies (year, day of week and the end time of each 30-minute intraday bar); all continuous variables are standardized to unit variance for interpretability.

[14]E.g., J.P.Morgan (2023) reports an increasing liquidation of 0DTE positions and a weaker return mean-reversion towards the end of a day; participants of the Systematic Investor Podcast name direct rebalancing as the preferred channel for 0DTE inventory management, www.toptradersunplugged.com, #275.

[15]Because the market makers' net open interest absorbs (and hence, is the mirror image of) the aggregate imbalances of other traders' groups, it suffices to conduct the tests using only the market makers' inventory

	$\ln RV_{t+1}$						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$OI^{\$\Gamma}_{MM,t,0DTE}$	-0.110***	-0.052***					-0.037***
	(0.011)	(0.009)					(0.010)
$OI^{\$\Gamma}_{MM,t,1DTE}$			-0.061***				-0.048***
			(0.009)				(0.012)
$OI^{\$\Gamma}_{MM,t,2-5DTE}$				-0.055***			-0.051***
				(0.007)			(0.010)
$OI^{\$\Gamma}_{MM,t,6-10DTE}$					-0.026***		-0.019**
					(0.007)		(0.009)
$OI^{\$\Gamma}_{MM,t,11-22DTE}$						-0.029***	-0.001
						(0.006)	(0.008)
$\ln RV_t$	0.660***	0.555***	0.530***	0.538***	0.545***	0.544***	0.536***
	(0.020)	(0.023)	(0.024)	(0.020)	(0.020)	(0.020)	(0.029)
$\ln RV_{t-1}$	0.174***	0.173***	0.188***	0.178***	0.184***	0.184***	0.169***
	(0.019)	(0.021)	(0.021)	(0.018)	(0.018)	(0.018)	(0.024)
$\ln RV_{t-2}$	-0.021	0.123***	0.145***	0.141***	0.147***	0.148***	0.099***
	(0.015)	(0.016)	(0.018)	(0.015)	(0.015)	(0.015)	(0.022)
Ret_t	-0.039***	-0.050***	-0.053***	-0.058***	-0.057***	-0.057***	-0.042***
	(0.008)	(0.009)	(0.009)	(0.008)	(0.008)	(0.008)	(0.011)
Ret_{t-1}	-0.009	-0.022***	-0.022***	-0.024***	-0.023***	-0.023***	-0.019**
	(0.006)	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.008)
Ret_{t-2}	-0.004	-0.009	-0.010	-0.010*	-0.008	-0.008	-0.012*
	(0.006)	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)	(0.007)
Year Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
Day of Week Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
Time Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.749	0.793	0.798	0.804	0.802	0.803	0.777
Obs.	4,920	4,920	4,920	6,160	6,160	6,160	3,680

Table 2: Market Maker Open Interest Gamma and Underlying Variance. This table reports the results of a regression of log of intraday variance over the 30-minute interval, following every 30-minute intraday time point, on the market maker open interest dollar gamma in SPXW options for different DTEs, denoted $OI^{\$\Gamma}_{MM,t,nDTE}$. The dependent variable and all continuous independent variables are standardized to unit variance. The regression controls for three lags of the dependent variable and of the returns for the same intervals. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2021 to 14/06/2023.

The results in Table 2 show that for all the expiry buckets, market makers' dollar gamma is negatively related to future realized variance, and even with all expiry buckets included in the regression jointly, most of them (except for 11-22 DTE) stay significant and negative. Lagged variance and realized return controls confirm an apparent persistence of realized variance and asymmetric volatility effect. In terms of economic magnitude, columns (2) and (7) indicate a decline in the underlying index variance by 5.2% and 3.7%, respectively, relative to its standard deviation following one standard deviation increase in the market makers' 0DTEs open interest gamma. Since market makers' open interest gamma is predominantly positive for most days and throughout the day in our sample, the coefficient estimates are consistent with market makers' delta-hedging activities, on average dampening intraday underlying variance, particularly for options with up to two weeks to expiration.

Next, we concentrate on 0DTEs and investigate the conditional effects of open interest gamma to ascertain whether the documented unconditional association changes when volatility is high, when current open interest gamma is negative, or whether the effect for negative return realizations is asymmetric. Table 3 shows the estimates of the following regression that includes a conditioning variable to the previous specification:

$$\ln RV_{t+1} = b_0 + OI^{\$\Gamma}_{MM,t,0DTE} \times (b_1 + b_2\theta_t) + \mathbf{CX} + \varepsilon_z, \tag{9}$$

where θ_t is one of the dummy variables, $Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$ indicating negative market maker's open interest gamma, $High\ RV_t$ indicating past realized variance above its sample median, and $Neg\ Ret_t$ indicating negative 30-minute return of the underlying index. All continuous variables before interaction are standardized to unit variance for interpretability.

The interactions of market makers' 0DTEs open interest gamma with dummies for high realized variance and negative realized return, respectively, have positive point estimates but are all insignificant and 2.5-5 times smaller than the base estimate. Thus, high variance and market declines slightly weaken but do not eliminate the volatility-dampening effect of market makers' 0DTEs open interest gamma. In contrast, the interaction coefficient for negative open interest gamma is positive and significant, changing the total effect of the $OI^{\$\Gamma}_{MM,t,0DTE}$ on future volatility from significantly negative to significantly *positive* when market makers are short gamma and we use time fixed effects in the regression.[16] The total effects are -0.016 and 0.085 in columns (1) and (2), with t-stats of -0.51 and 3.23, respectively. This result is intriguing

[16]Time-of-day fixed effects are crucial for the result.

	$\ln RV_{t+1}$					
	(1)	(2)	(3)	(4)	(5)	(6)
$OI^{\$\Gamma}_{MM,t,0DTE}$	-0.115***	-0.081***	-0.116***	-0.064***	-0.102***	-0.049***
	(0.018)	(0.014)	(0.015)	(0.011)	(0.015)	(0.011)
$OI^{\$\Gamma}_{MM,t,0DTE} \times Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$	0.100***	0.166***				
	(0.035)	(0.030)				
$OI^{\$\Gamma}_{MM,t,0DTE} \times High\ RV_t$			0.004	0.028		
			(0.024)	(0.020)		
$OI^{\$\Gamma}_{MM,t,0DTE} \times Neg\ Ret_t$					-0.023	-0.008
					(0.022)	(0.018)
$\ln RV_t$	0.642***	0.531***	0.640***	0.491***	0.690***	0.566***
	(0.024)	(0.024)	(0.033)	(0.030)	(0.028)	(0.029)
$\ln RV_{t-1}$	0.176***	0.179***	0.189***	0.208***	0.144***	0.152***
	(0.023)	(0.023)	(0.029)	(0.027)	(0.025)	(0.026)
$\ln RV_{t-2}$	-0.012	0.126***	-0.038	0.124***	-0.008	0.144***
	(0.019)	(0.018)	(0.026)	(0.024)	(0.020)	(0.021)
Ret_t	-0.052***	-0.067***	-0.112***	-0.129***	-0.011	-0.012
	(0.009)	(0.009)	(0.023)	(0.021)	(0.016)	(0.017)
Ret_{t-1}	-0.007	-0.024***	0.046**	0.022	-0.004	-0.023***
	(0.010)	(0.009)	(0.018)	(0.016)	(0.008)	(0.008)
Ret_{t-2}	-0.011	-0.018**	-0.036*	-0.041**	-0.001	-0.012
	(0.009)	(0.008)	(0.019)	(0.018)	(0.008)	(0.008)
$Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$	0.053*	0.044				
	(0.030)	(0.027)				
$High\ RV_t$			0.082*	0.087**		
			(0.048)	(0.043)		
$Neg\ Ret_t$					-0.105**	-0.096**
					(0.046)	(0.043)
Year Dummies	No	Yes	No	Yes	No	Yes
Day of Week Dummies	No	Yes	No	Yes	No	Yes
Time Dummies	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.749	0.794	0.751	0.795	0.750	0.794
Obs.	4,920	4,920	4,920	4,920	4,920	4,920

Table 3: Conditional Effect of Market Maker Open Interest Gamma on Underlying Variance. This table reports the results of a regression of log of intraday variance over the 30-minute interval, following every 30-minute time point on the market maker SPXW 0DTE open interest dollar gamma ($OI^{\$\Gamma}_{MM,t,0DTE}$) and its interaction with dummy variables indicating negative last 30-minute index return ($Neg\ Ret_t$), last 30-minute variance of the underlying index above its sample median ($High\ RV_t$), and negative open interest gamma ($Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$). The dependent variable and all continuous independent variables before interaction are standardized to unit variance for interpretability. The regression controls for three lags of the dependent variable and 30-minute realized returns over the same intervals. All control variables are interacted with conditioning dummies, but their coefficient are suppressed for brevity. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2021 to 14/06/2023.

and indicates that when market makers are net short in 0DTEs, their open interest gamma can be positively related to subsequent variance, suggesting that in this case volatility timing could potentially offset or even dominate the delta-hedging effect.

While the observed unconditional negative association between market makers' inventory gamma and future variance is consistent with the delta-hedging mechanism, it could also be explained by market participants' superior volatility timing abilities when trading against market makers. On the other hand, the positive association conditional on negative inventory gamma is consistent with market makers' superior volatility timing. To further understand these volatility information stories, we examine whether market makers' 0DTEs open interest gamma changes in response to the prevailing intraday volatility regime. We adapt Ni, Pearson, Poteshman, and White (2021) approach and regress the future level and first difference of market makers' 0DTEs open interest gamma on the underlying variance and returns, separately conditioning on *positive* and *negative* current open interest gamma. If market makers' inventory gamma changes in response to volatility information, we should observe that these variables, which reflect information about future variance, significantly predict the subsequent market makers' 0DTEs open interest gamma. The results summarized in Table 4 indicate that market makers inventory gamma does not significantly change in response to the intraday volatility information, and a lack of a robust link between negative market makers' open interest gamma and subsequent variance can stem from any of the reasons we mentioned for the given scenario.

In our sample period, market makers hold on average and in 70% of the time a positive gamma inventory, so the delta-hedging channel dominates in the unconditional results in Table 2. To check how market makers act in times of elevated uncertainty, we conduct additional analysis that provides further evidence supporting the delta-hedging causal channel. We build on the fact that days with important macroeconomic announcements during regular trading hours are known to feature substantial uncertainty that can pose significant risks to market makers. As such, market makers, which delta-hedge their 0DTEs inventory, are more likely to do so on such high uncertainty days relative to other days. Therefore, if the negative association between the market maker's open interest gamma and underlying variance is due to delta-hedging activities, we expect it to be especially pronounced on such days.

	$OI^{\$\Gamma}_{MM,t,0DTE} \geq 0$				$OI^{\$\Gamma}_{MM,t,0DTE} < 0$			
	$OI^{\$\Gamma}_{MM,t+1,0DTE}$		$\Delta OI^{\$\Gamma}_{MM,t+1,0DTE}$		$OI^{\$\Gamma}_{MM,t+1,0DTE}$		$\Delta OI^{\$\Gamma}_{MM,t+1,0DTE}$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$OI^{\$\Gamma}_{MM,t,0DTE}$	0.968***	0.967***			0.723***	0.720***		
	(0.042)	(0.043)			(0.067)	(0.067)		
$OI^{\$\Gamma}_{MM,t-1,0DTE}$	-0.008	-0.006			0.140*	0.142*		
	(0.055)	(0.055)			(0.074)	(0.074)		
$OI^{\$\Gamma}_{MM,t-2,0DTE}$	-0.036	-0.038			-0.047	-0.045		
	(0.037)	(0.037)			(0.036)	(0.036)		
$\Delta OI^{\$\Gamma}_{MM,t,0DTE}$			0.016	0.015			-0.094	-0.097
			(0.037)	(0.037)			(0.064)	(0.064)
$\Delta OI^{\$\Gamma}_{MM,t-1,0DTE}$			0.015	0.016			0.051	0.049
			(0.029)	(0.029)			(0.036)	(0.036)
$\Delta OI^{\$\Gamma}_{MM,t-2,0DTE}$			-0.065*	-0.066*			-0.038	-0.036
			(0.037)	(0.037)			(0.028)	(0.029)
$\ln RV_t$	0.002	-0.000	0.022	0.021	0.021	0.024	0.042	0.048
	(0.017)	(0.018)	(0.046)	(0.048)	(0.025)	(0.026)	(0.044)	(0.045)
$\ln RV_{t-1}$	0.012	0.011	0.032	0.029	-0.005	-0.009	-0.007	-0.013
	(0.017)	(0.017)	(0.045)	(0.046)	(0.036)	(0.037)	(0.064)	(0.065)
$\ln RV_{t-2}$	-0.009	-0.006	0.011	0.013	0.050	0.048	0.088	0.085
	(0.017)	(0.017)	(0.045)	(0.045)	(0.033)	(0.033)	(0.059)	(0.059)
Ret_t		0.002		0.011		0.016		0.026
		(0.006)		(0.017)		(0.015)		(0.026)
Ret_{t-1}		-0.008		-0.010		0.008		0.017
		(0.005)		(0.014)		(0.012)		(0.021)
Ret_{t-2}		-0.001		-0.001		-0.022**		-0.040**
		(0.005)		(0.014)		(0.010)		(0.018)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Day of Week Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.861	0.861	0.014	0.013	0.692	0.692	0.041	0.042
Obs.	3,116	3,116	3,005	3,005	1,311	1,311	1,297	1,297

Table 4: Market Makers' 0DTEs Open Interest Gamma Conditional on Volatility Information. The table analyzes whether market makers' 0DTEs open interest gamma changes in response to information about future volatility. We regress the $t+1$ level of market makers' 0DTEs open interest gamma denoted $OI^{\$\Gamma}_{MM,t+1,0DTE}$ (columns (1), (2), (5) and (6)) and its first difference denoted $\Delta OI^{\$\Gamma}_{MM,t+1,0DTE}$ (columns (3), (4), (7) and (8)) on their respective lags and three lags of log realized variances and realized returns. We condition the tests on the positive (first four columns) and the negative (last four columns) current open interest gamma $OI^{\$\Gamma}_{MM,t,0DTE}$. The dependent variable and all continuous independent variables are standardized to unit variance. Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is 01/2021 to 14/06/2023.

To conduct the analysis, we identify four macro announcements released during the regular trading hours, namely the Federal Open Market Committee (FOMC) Statements (issued around 14:00), FOMC Meeting Minutes (around 14:00), published typically several weeks after the Statements, Fed Funds Rate announcements (around 14:00), and 30-year Bond Auctions (approximately at 13:01). While the first three announcements are extremely important because of their information content and occasional 'surprises' for the markets, the last one is routine,

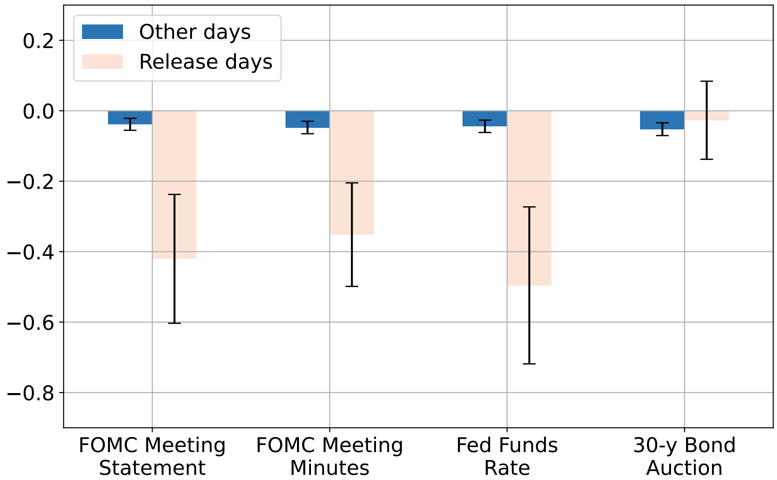

Figure 4: Announcement Day Effects of Market Maker Open Interest. The figure shows the coefficient estimates for the effect of market maker SPXW 0DTEs open interest dollar gamma ($OI^{\$\Gamma}_{MM,t,0DTE}$) on intraday variance, conditional on macroeconomic release days. We regress the log of 30-minute variance, following every 30-minute time point, on $OI^{\$\Gamma}_{MM,t,0DTE}$ and its interactions with dummy variables, indicating a given macroeconomic release day, and plot the total effect of $OI^{\$\Gamma}_{MM,t,0DTE}$. The dependent variable and all continuous independent variables before interaction are standardized to unit variance, and we use the same control as in Table 2, column (2). The plotted 95% confidence intervals use the Newey and West (1987) standard errors with five lags. The sample period is from 01/2021 to 14/06/2023.

and does not have much market impact. Using regression (9) with the day-of-announcement dummy as the interaction term (instead of θ_t), we compute the total open interest gamma effects (i.e., either the base coefficient or adding up the base and interaction term coefficients). Figure 4 plots these estimates and their confidence intervals. We observe that on the days when market makers face high intraday uncertainty and, hence, have a greater incentive to keep inventory risk under tight control, the negative association between market makers' open interest gamma and subsequent variance is markedly more negative across the more important releases.

4.1.2 Start-of-Day Open Interest and Daily Variance

In this section we analyze the impact of total open interest on subsequent volatility. This is motivated by the possibility that some group of traders, not necessarily just market makers, delta hedge their inventory. One can hypothesize that short gamma positions have a stronger motive for maintaining a dynamic hedge because negative convexity leads to losses for short gamma positions in the case of large market moves.

We only observe total open interest at the market open. It is not possible to reconstruct intraday total open interest at a higher frequency because the open-close volume data do not contain information about open-close trades that take place between traders of similar category. Nevertheless, we can project future variance onto total 0DTE open interest gamma at the market open to establish whether morning gamma is associated with higher or lower subsequent intraday volatility.

For the test we use log realized variance $\ln RV_d^{day}$ computed from equation (2), the start-of-day open interest dollar gamma $OI^{\$\Gamma}_{d:sod,dte}$ computed from equation (3) and aggregated for the pre-defined DTE buckets and both SPXW and SPY options, to capture total rebalancing risk due to fluctuations in the underlying market index. We estimate the following regression:

$$\ln RV_d^{day} = b_0 + OI^{\$\Gamma}_{d:sod,dte} \times (b_1 + b_2 \ln RV_d^{on} + b_3 \ln RV_{d-1}^{day}) + \mathbf{CX} + \varepsilon_d, \tag{10}$$

where $\mathbf{X}$ is a vector of controls including overnight variance RV_d^{on}, five lags of intraday variance RV_d^{day} (i.e., lags of the dependent variable), and year dummies.[17] We standardize all continuous variables before interaction to unit variance. Table 5 provides no indication that total risk in 0DTEs is associated with the propagation of the overnight and lagged intraday variances to the subsequent daily variance. The coefficients on the interaction between the gamma levels and variances are insignificant for 0DTEs. For the other DTE buckets, we have some weak evidence that high gamma and overnight variance interaction terms are linked to a lower variance the next day. Moreover, open interest gamma in the morning of day d is mostly *negatively* related

[17]Including more lags of overnight variance has no effect on magnitude and significance of other coefficients, so we kept only one. Excluding the interaction of gamma with lagged intraday variance does not materially change the results. In Robustness Section 5 we also estimate a similar regression without interactions but including lagged daily trading volume in 0DTEs and lagged start-of-day open interest gamma. The volume coefficient turns insignificant once we control for lagged dependent variable.

	$\ln RV_d^{day}$				
	0DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI_{dte,d}^{\$\Gamma} \times \ln RV_d^{on}$	-0.006	-0.036*	-0.009	-0.029**	-0.039***
	(0.015)	(0.019)	(0.013)	(0.014)	(0.015)
$OI_{dte,d}^{\$\Gamma} \times \ln RV_{d-1}^{day}$	-0.008	-0.013	-0.018	-0.021*	0.000
	(0.019)	(0.018)	(0.013)	(0.013)	(0.013)
$OI_{dte,d}^{\$\Gamma}$	-0.176	-0.318*	-0.327**	-0.451***	-0.195
	(0.189)	(0.173)	(0.138)	(0.141)	(0.142)
$\ln RV_d^{on}$	0.066**	0.063**	0.064***	0.089***	0.108***
	(0.030)	(0.030)	(0.022)	(0.022)	(0.024)
$\ln RV_{d-1}^{day}$	0.550***	0.561***	0.560***	0.571***	0.548***
	(0.038)	(0.035)	(0.030)	(0.029)	(0.030)
$\ln RV_{d-2}^{day}$	0.127***	0.180***	0.126***	0.138***	0.142***
	(0.030)	(0.032)	(0.023)	(0.023)	(0.024)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.745	0.751	0.726	0.722	0.718
Obs.	1,447	1,447	2,661	2,769	2,801

Table 5: Volatility Propagation by Open Interest Gamma. This table reports the results of a regression of log of intraday variance on the level of overnight variance and lagged intraday variance both interacted with start-of-day open interest dollar gamma by DTE buckets, using the specification in (10). Start-of-day open interest is converted to dollar gamma $OI_{d:sod,dte}^{\$\Gamma}$ at 10:00 each day and aggregated for SPY and SPXW options with moneyness levels in $[0.5, 1.5]$ for each DTE bucket. Realized variances are computed from intraday and overnight returns for SPX index. Dependent and independent variables before interaction are standardized to unit variance. Five lags of dependent variable are included, but only two are shown for brevity. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2012 to 14/06/2023.

to the intraday volatility, and the coefficient is significant for intermediate maturity buckets. Overall, we do not find evidence that higher open interest gamma levels destabilize prices and contribute to clustered volatility shocks.

4.2 Trading Activity

4.2.1 Intraday Return Dynamics

We analyze intraday market returns to assess how sudden spikes in 0DTE trading volume shape subsequent large return realizations. We are interested in the accumulation of realized returns in either the positive or negative direction following a volume jump, with the negative reaction expected to have stronger implications for market stability. While high volume is often associated with high return volatility, we want to ascertain whether sharp jumps in 0DTE volume typically precede and potentially cause large underlying returns.

To obtain 0DTE options volume, we sum the dollar-delta volumes for SPY and SPXW options at each 1-minute intraday interval and then convert it to log volume $v_t^{\$\Delta} = \ln Vol_t^{\$\Delta}$. We identify jumps in intraday 0DTE trading volume by point in time t with the 1-minute changes in trading volume $(v_t^{\$\Delta} - v_{t-1}^{\$\Delta})$ larger than three times its standard deviation on a given day. We use the 5-minute cumulative returns (from $t+1$ to $t+5$) as a measure of market reaction to a volume shock at time t and then test whether the market reaction differs conditional on having experienced a sizeable 0DTE volume jump and whether it depends on the realized return before and during the 0DTE trading volume jump.

Figure 5 plots the distribution densities of the 5-minute cumulative returns conditional on jump vs. no jump in 0DTEs volume and separately for four sub-periods. Visually, the distribution conditional on volume jumps has slightly fatter tails on both sides of the return realizations, but we do not observe drastic differences in the distributions or out-of-the-ordinary market reaction following 0DTE volume jumps. We further test these observations more formally. First, we run two non-parametric tests (k-sample Anderson-Darling and two-sample Kolmogorov-Smirnov tests) to see whether both samples are drawn from the same distribution. Second, because we are especially interested in the tails of the distribution, we run a series of quantile regressions analyzing how relatively infrequent realizations of returns depend on 0DTE volume jumps dummy in interaction with year fixed effect and cumulative market returns before the volume jump. Such specification allows us to directly evaluate claims that large underlying market moves are propagated through 0DTE trading, especially in recent years.

Table 6 shows the results of the non-parametric tests for the conditional samples. We fail to reject that the samples are drawn from the same distribution for all sub-periods and both tests. k-sample Anderson-Darling is more suitable for our purpose because, compared to the

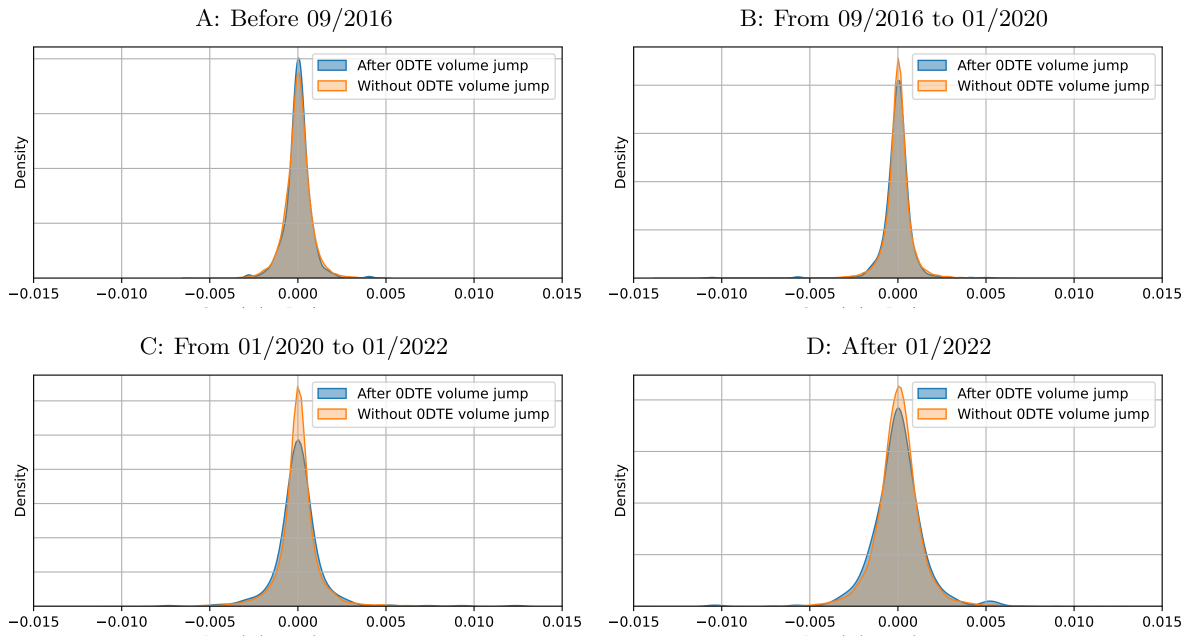

Figure 5: Cumulative Returns Conditional on 0DTE Volume Jump. The figure shows the distribution density of 5-minute returns (from $t+1$ to $t+5$) conditional on having a large jump in 0DTE volume at t and not having such a jump, for four sub-periods. We sample non-overlapping observations, skipping at least five minutes between each selected t point. The sample period is from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration.

Kolmogorov-Smirnov, it puts more weight on the tails of the distributions. Table 7 presents

	KS Statistic	p-val	AD Statistic	p-val
Before 09/2016	0.062	0.167	1.064	0.119
From 09/2016 to 01/2020	0.035	0.324	0.547	0.197
From 01/2020 to 01/2022	0.036	0.615	-0.751	0.250
After 01/2022	0.028	0.858	-0.644	0.250

Table 6: Testing Conditional Cumulative Return Samples. This table reports the results of the two-sample Kolmogorov-Smirnov and k-sample Anderson-Darling tests (Scholz and Stephens 1987) for the distributions of 5-minute cumulative returns (from $t+1$ to $t+5$) conditional on having a large jump in 0DTE volume at t and not having such a jump, for four sub-periods. We sample non-overlapping observations in the sample period from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration.

the results of the quantile regressions for selected percentiles on both sides of the distribution, using the period before 2020 as the base. We include all double and triple interaction terms in the regression but concentrate on past cumulative return and 0DTE volume jump, with and without year dummy interaction. We report only the interaction term coefficients central to our analysis for brevity. In all cases, we fail to reject the null that there is no propagation of past returns by 0DTE volume jumps—the interactions of past return and volume jump, with and without year dummies, are all insignificant. There is limited evidence that the 0DTE volume jump is inversely associated with positive future returns (Q90 and Q95), but the relationship is not mediated by the past returns preceding the 0DTE volume jump. In short, there is no evidence that 0DTE trading *propagates* market moves.

	Q1	Q5	Q10	Q90	Q95	Q99
0DTE Volume Jump	-0.007	0.001	0.002	-0.010*	-0.019**	-0.037
	(0.024)	(0.009)	(0.006)	(0.005)	(0.008)	(0.024)
Past Return	1.950	1.044	1.090	-6.213***	-6.193**	-4.226
	(11.343)	(3.332)	(1.825)	(1.613)	(3.029)	(12.195)
0DTE Volume Jump x Past Return	-51.607	-4.357	-0.776	24.122	24.811	17.382
	(108.178)	(23.700)	(12.491)	(15.895)	(32.455)	(123.464)
0DTE Volume Jump x Year 2021	0.011	-0.003	0.010	0.016	0.031	0.017
	(0.061)	(0.022)	(0.014)	(0.013)	(0.021)	(0.073)
0DTE Volume Jump x Year 2022	-0.008	-0.002	-0.002	0.004	0.009	0.157***
	(0.051)	(0.019)	(0.012)	(0.011)	(0.018)	(0.057)
0DTE Volume Jump x Year 2023	-0.005	-0.053**	-0.036**	0.040**	0.090***	0.152*
	(0.077)	(0.027)	(0.017)	(0.016)	(0.026)	(0.080)
Past Return x 0DTE Volume Jump x Year 2021	82.265	10.533	-3.995	-21.647	-33.479	-25.417
	(265.968)	(34.617)	(26.102)	(30.363)	(65.455)	(363.127)
Past Return x 0DTE Volume Jump x Year 2022	66.997	3.583	13.683	-17.698	-22.067	4.772
	(112.238)	(26.871)	(15.082)	(17.605)	(34.433)	(129.624)
Past Return x 0DTE Volume Jump x Year 2023	78.544	18.195	1.174	-6.632	13.700	38.228
	(130.054)	(42.283)	(22.504)	(22.901)	(39.768)	(140.295)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	84,645	84,645	84,645	84,645	84,645	84,645

Table 7: Quantile Regressions of Intraday Returns. This table reports the results of the quantile regressions of the selected percentiles (1/5/10/90/95/99) of the five-minute cumulative returns from $t+1$ to $t+5$ on the dummy for the 0DTE Volume Jump at t, past five-minute cumulative return from $t-4$ to t (Past Return), year dummies, and double and triple interactions of the variables. We omit some double interactions from the table for space reasons. We sample non-overlapping observations, skipping at least five minutes between each selected t point. The sample period is from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration. Standard errors are in parentheses.

4.2.2 Underlying and Options Markets Integration

Next, we examine both the underlying and options markets jointly by studying how intraday trading in both markets is related to realized price movements of the underlying asset. To this end, we estimate Vector-Auto-Regressions (VARs) on three key time-series: 0DTE options trading volume, underlying volume, and Realized Variance of the underlying. We seek to understand the joint dynamics of these variables, their contemporaneous correlation, and how the dynamic relationship between them has changed over time as 0DTE trading has become more prevalent.

Because trading volumes in the underlying and options markets are interrelated and linked to realized returns through delta-hedging, we model their dynamics jointly using a structural VAR. Following Koop, Pesaran, and Potter (1996) and Pesaran and Shin (1998), we analyze responses to shocks in the system using generalized impulse response functions (gIRF), which account for the correlation of structural shocks in the system and are invariant to the ordering of the time-series (Pesaran 2015 and Wiesen and Beaumont 2023).

In order to compute volume for the underlying, we use both intraday 1-minute bar data for SPY, and the front-month contract of the S&P500 E-mini Futures, ES. At the one-minute frequency, for each bar within the regular day session (from 9:31 to 16:00), we add up dollar trading volume $V_j^{\$}$ for both j = SPY and ES to obtain aggregate volume $V_{d:t}^{\$}$ and convert it to log $v_{d:t}^{\$} = \ln V_{d:t}^{\$}$. For the volume of 0DTE options, we proceed in the same way, adding dollar delta volumes for each one-minute for SPY and SPXW options and then convert it to log volume $v_{d:t}^{\$\Delta} = \ln V_{d:t}^{\$\Delta}$. We also compute simple SPY returns $R_{d:t}$ over the matching time intervals and use 1-minute squared returns as the instantaneous variance proxy $\sigma_{d:t}^2 = R_{d:t}^2$. To maintain stationarity in the time-series, we use the first differences of the volume variables for estimation. We also standardize all variables daily to unit variance.

Because we want to focus on the variables' intraday association, we estimate their joint dynamics each day, compute the generalized impulse response functions, and use the distribution of these gIRFs over a specified period to get the average impulse responses and their confidence bounds. We split the sample into two sub-periods: 2012-2019, characterized by relatively less 0DTE volume, and 2020-2023, during which 0DTE trading volumes rapidly increased. As expected, the trading volume differences for 0DTEs and the underlying are highly correlated, especially in the latter period: the correlation goes from 0.27 in 2012-2019 to 0.39 in 2020-2023. The correlations between the variance and volume variables are initially higher for the underlying market than for 0DTEs (0.14 vs. 0.08). However, in the latter period, both correlations almost perfectly align at the level of 0.14–0.15.

We estimate the following structural model daily as a dynamic reduced-form VAR at 1-minute frequency and using $n = 5$ lags:

$$\begin{aligned}
\sigma^2_{d:t} &= c_0 + \sum_{l=1}^{n} c_{1,l} \Delta v^{\$}_{d:t-l} + \sum_{l=1}^{n} c_{2,l} \Delta v^{\$\Delta}_{d:t-l} + \sum_{l=1}^{n} c_{3,l} \sigma^2_{d:t-l} + e_{\sigma^2,d:t}, \\
\Delta v^{\$\Delta}_{d:t} &= b_0 + \sum_{l=1}^{n} b_{1,l} \Delta v^{\$}_{d:t-l} + \sum_{l=1}^{n} b_{2,l} \Delta v^{\$\Delta}_{d:t-l} + \sum_{l=1}^{n} b_{3,l} \sigma^2_{d:t-l} + e_{\Delta v^{\$\Delta},d:t}, \\
\Delta v^{\$}_{d:t} &= a_0 + \sum_{l=1}^{n} a_{1,l} \Delta v^{\$}_{d:t-l} + \sum_{l=1}^{n} a_{2,l} \Delta v^{\$\Delta}_{d:t-l} + \sum_{l=1}^{n} a_{3,l} \sigma^2_{d:t-l} + e_{\Delta v^{\$},d:t}.
\end{aligned} \tag{11}$$

We use the estimation output to compute generalized impulse response functions for one-standard deviation shocks to the selected variables.[18] For each sub-period 2012-2019 and 2020-2023, we obtain the average values and the confidence bounds (5th and 95th percentiles) from the collection of intraday gIRFs for five time steps. Figure 6 shows three key impulse response

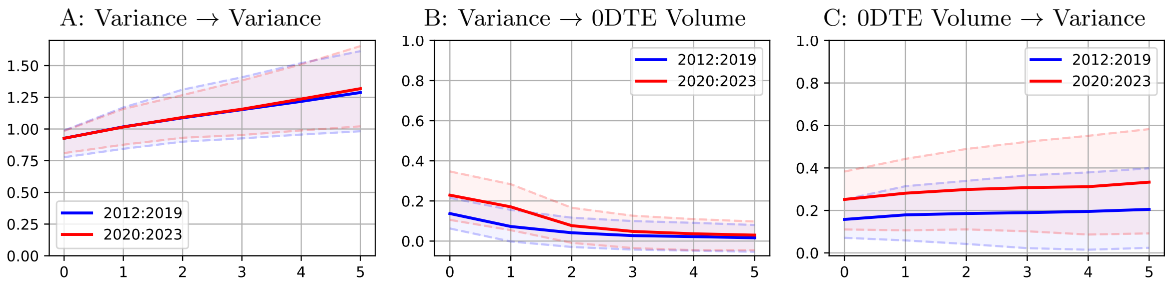

Figure 6: 0DTE Volume and Underlying Variance Generalized Cumulative Impulse Response Functions. The figure shows the average generalized impulse response functions with confidence bounds (5th and 95th percentiles of empirical daily distribution) for the VAR system in (11) estimated daily with $n = 5$ lags for one-minute frequency. The averages and percentiles are computed for 2012-2019 (plotted in blue) and 2020-2023 (plotted in red). The response is calculated for one standard deviation shock to a given variable. The variables are winsorized at 0.01/0.99 levels for the whole sample period and standardized daily to unit variance. The sample period is from 01/2012 to 14/06/2023.

functions. To interpret the plots, note that a difference between the two time periods will show as a parallel shift in the gIRFs *if* the change in the gIRF is driven by a *contemporaneous* cor-

[18]Note that one can easily extend the analysis to compute joint impulse response functions as in Wiesen and Beaumont (2023). However, it requires an assumption about joint shocks, which adds unnecessary complexity.

relation. We see this in the last plot (Panel C), where the average post-2020 gIRF is shifted upwards by an amount corresponding to the 0-frequency shift, indicating the response of market variance to shocks in 0DTE volume is entirely driven by an increase in the 0-frequency, contemporaneous correlation between these variables. We observe no change between the periods for the Variance-to-variance IRF (Panel A). Panel B shows how variance shocks impact 0DTE volume. Here, we see a slight increase at the 0, 1, and 2-minute horizon, followed by a near-zero difference at longer horizons.

Figure 6 also shows confidence bands for the gIRFs computed from their empirical distribution. We see that these bands overlap and, thus, suggest that we cannot reject the null that the dynamic relationship implied by the VARs is unchanged from the pre-to post-2020 periods. The point estimates, however, imply a small but statistically insignificant increase in the joint correlation between the three variables at the contemporaneous, 0-frequency horizon. We interpret this to suggest an increase in market integration over time. For example, following a one standard deviation shock to 0DTE trading, the underlying index variance rises from about 0.18 standard deviation units in the 2012-2019 sub-period, increasing to 0.26 standard deviation units in 2020-2023. Although these numbers imply a 1.5 times stronger response in the latter period, the magnitude is economically negligible and statistically insignificant.

5 Robustness and Extensions

We conduct several tests to assess the robustness of our findings, reconcile some of our results with the existing literature, and collect the additional results in the Online Appendix.

We extend our analysis of market maker open interest gamma effect on underlying variance to include "speed" and "charm" in Section IA.1.1, and the results indicate that these components do not propagate past volatility or negative market shocks. To test the sensitivity of the results for the intraday market maker's open interest effects on intraday variance, we vary the period for variance computation. Tables IA.2 and IA.3 report the results of the regressions using variances over 10 minute instead of the 30 minutes in the main analysis. The main inferences do not change. We also test the sensitivity of the results for regressions of intraday log variance on the start-of-day open interest gamma and its interactions with overnight and lagged daily variances. Instead of using full-day variance as the dependent variable, we compute intraday variance from 10:00 (the point at which we observe the start of the day open interest gamma) to 14:00 or 12:00. Table IA.4 reports the numbers for the variance between 10:00 and 14:00 (the other time frame is available upon request) and the results are similar to the original table. Splitting the sample into periods with low and high 0DTE trading volume does not change the main inferences of our analysis on the propagation of volatility by the start-of-day open interest gamma in 0DTEs—Table IA.5 shows the results for 2012-2019 and 2020-2023.

In Section IA.1.2, we analyze the discrepancies between our results and findings of the positive effect of 0DTE trading volume on the underlying variance in Brogaard, Han, and Won (2023). Table IA.6 shows the results of a regression of daily variance on lagged 0DTE volume and open interest gamma, with and without controls for lagged variance. A significant positive coefficient on lagged volume turns insignificant with lagged variance controls. The reported results vary considerably depending on the variables pre-processing and controls (e.g., applying log transformation to the dependent variable, controlling for lags of overnight variance in addition to daily variance, using volume ratio instead of log volume), and because of lack of robustness of such regressions, we would be cautious in interpreting these numbers and their statistical properties.

Section IA.1.3 provides additional analysis of sensitivity of impulse response functions to 0DTE market activity in Table IA.7, and also extends the market integration analysis with VAR to longer-term expiry buckets, showing in Figure IA.1 that the increasing correlation of intraday volume and variance shocks is driven predominantly by short-term expiry options with less than a week to expiry.

In Section IA.1.4, we provide additional results on the returns and variance risk premiums in 0DTE options, and Section IA.1.5 analyzes potential uses of short-term options on days with elevated uncertainty, such as Federal Open Market Committee days.

6 Conclusion

Following the introduction of weekly options with daily expiration by Cboe, ultra-short maturity options have surged in popularity in recent years, with the daily trading volume in zero days to expiration options (0DTEs) increasing more than tenfold from its 2012 level. As a result, several large market participants have expressed concerns that the ballooning 0DTE trading could intensify price moves as the re-adjustment of delta hedges in the same direction as the underlying market could amplify price moves.

Following the basic causal mechanism from inventory delta-hedging to trading flows and price reaction, we document that market makers' intraday 0DTE open interest gamma is negatively associated with future short-term volatility. One interpretation of this evidence is that there is a volatility dampening effect arising from market makers' predominantly long inventory gamma. As a result, market makers trade underlying assets against market shocks when hedging their inventory. The evidence is also consistent with non-market makers trading on information that allows them to time volatility bets. Furthermore, we find no evidence that start-of-day aggregate open interest gamma propagates past daily and overnight volatility unto the future, and for options with one day to two weeks to expiry, it is negatively associated with the subsequent daily volatility.

We further analyze how spikes in 0DTEs trading volumes shape the subsequent intraday market index returns. We do not find significant differences between distributions on days with and without volume jumps. More so, extreme quantiles of the intraday return distributions are not significantly related to the interaction of 0DTE volume and preceding returns. Nonetheless, we observe stronger integration of the underlying and 0DTE option markets, with more correlated trading and simultaneous spikes in volumes and return variance.

In conclusion, while our results suggest that market makers' 0DTE positions do not propagate large market moves and are linked to a lower, not higher, short-term variance, the results are conditioned on a period when market makers, on average, held long positions in 0DTEs. Thus, while concerns over a potential hedging-based destabilization of underlying markets cannot be substantiated based on our evidence and within our sample period, we do not extrapolate to a scenario where the market makers' inventories become very negative. Future studies could assess the limitations of the existing 0DTEs regulatory frameworks (e.g., intraday exchange margin and mark-to-market mechanisms) and their potential effect on market stability. Such analysis could yield insights that can aid the design of optimal risk management and regulatory practices, which are beyond the scope of the current study.

References

Adams, G., J.-S. Fontaine, and C. Ornthanalai, 2024, "The Market for 0-Days-to-Expiration: The Role of Liquidity Providers in Volatility Attenuation," Working Paper Government of Canada - Bank of Canada, University of Toronto - Rotman School of Management.

Ai, H., L. J. Han, X. N. Pan, and L. Xu, 2022, "The cross section of the monetary policy announcement premium," *Journal of Financial Economics*, 143(1), 247–276.

Aït-Sahalia, Y., M. Karaman, and L. Mancini, 2020, "The term structure of equity and variance risk premia," *Journal of Econometrics*, 219(2), 204–230, Annals Issue: Econometric Estimation and Testing: Essays in Honour of Maxwell King.

Almeida, C., G. Freire, and R. Hizmeri, 2023, "0DTE Asset Pricing," Working paper, Princeton University.

Anderegg, B., F. Ulmann, and D. Sornette, 2022, "The impact of option hedging on the spot market volatility," *Journal of International Money and Finance*, 124, 102627.

Bali, T. G., and H. Zhou, 2016, "Risk, Uncertainty, and Expected Returns," *Journal of Financial and Quantitative Analysis*, 51(3), 707–735.

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

Bandi, F. M., N. Fusari, and R. Renò, 2023, "0DTE option pricing," *Working paper*.

Barbon, A., and A. Buraschi, 2020, "Gamma fragility," Working Paper Imperial College Business School 05.

Beckmeyer, H., N. Branger, and L. Gayda, 2023, "Retail Traders Love 0DTE Options... but should they?," *working paper*.

Bollerslev, T., G. Tauchen, and H. Zhou, 2009, "Expected Stock Returns and Variance Risk Premia," *Review of Financial Studies*, 22(11), 4463–4492.

Brogaard, J., J. Han, and P. Y. Won, 2023, "How does Zero-Day-to-Expiry Options Trading Affect the Volatility of Underlying Assets?," *Working Paper, University of Utah*.

Bryzgalova, S., A. Pavlova, and T. Sikorskaya, 2023, "Retail Trading in Options and the Rise of the Big Three Wholesalers," *The Journal of Finance*, 78(6), 3465–3514.

Carr, P., and L. Wu, 2009, "Variance Risk Premiums," *Review of Financial Studies*, 22(3), 1311–1341.

Cboe, 2023, "Volatility Index Methodology: Cboe Volatility Index," working paper, Cboe Global Indices, LLC.

Cieslak, A., A. Morse, and A. Vissing-Jorgensen, 2019, "Stock returns over the FOMC cycle," *The Journal of Finance*, 74(5), 2201–2248.

Dew-Becker, I., and S. Giglio, 2023, "Risk Preferences Implied by Synthetic Options," NBER Working Papers 31833, National Bureau of Economic Research, Inc.

Dew-Becker, I., S. Giglio, A. Le, and M. Rodriguez, 2017, "The price of variance risk," *Journal of Financial Economics*, 123(2), 225–250.

Eraker, B., and Y. Wu, 2017, "Explaining the Negative Returns to VIX Futures and ETNs: An Equilibrium Approach," *Journal of Financial Economics*, 125(1), 72–98.

Frey, R., 1998, "Perfect option hedging for a large trader," *Finance and Stochastics*, 2, 115–141.

Frey, R., and A. Stremme, 1997, "Market Volatility and Feedback Effects from Dynamic Hedging," *Mathematical Finance*, 7(4), 351–374.

Hansen, P. R., and A. Lunde, 2005, "A Realized Variance for the Whole Day Based on Intermittent High-Frequency Data," *Journal of Financial Econometrics*, 3(4), 525–554.

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

Hu, J., A. Kirilova, and D. Muravyev, 2023, "Options Market Makers," Working Paper, Michigan State University, Canadian Derivatives Institute.

Jarrow, R. A., 1994, "Derivative Security Markets, Market Manipulation, and Option Pricing Theory," *The Journal of Financial and Quantitative Analysis*, 29(2), 241–261.

Johannes, M. S., A. Kaeck, N. Seeger, and N. Shah, 2024, "Expected 1DTE Option Returns," Working paper GSB, Columbia University.

J.P.Morgan, 2023, "0DTE Options: Recent Observations on Intraday Price Patterns," Technical report, J.P.Morgan, Global Quantitative & Derivatives Strategy.

Koop, G., M. Pesaran, and S. M. Potter, 1996, "Impulse response analysis in nonlinear multivariate models," *Journal of Econometrics*, 74(1), 119–147.

Kyle, A. S., 1985, "Continuous Auctions and Insider Trading," *Econometrica*, 53(6), 1315–35.

Lipson, M., D. Tomio, and J. Zhang, 2023, "A Real Cost of Free Trades: Retail Option Trading Increases the Volatility of Underlying Securities," *Working paper*.

Londono, J. M., and M. Samadi, 2024, "The Price of Macroeconomic Uncertainty: Evidence from Daily Option Expirations," Working Paper Board of Governors of the Federal Reserve System.

Newey, W. K., and K. D. West, 1987, "A Simple, Positive-semidefinite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix," *Econometrica*, 55(3), 703–708.

Ni, S. X., N. D. Pearson, A. M. Poteshman, and J. White, 2021, "Does option trading have a pervasive impact on underlying stock prices?," *The Review of Financial Studies*, 34(4), 1952–1986.

Pesaran, H., and Y. Shin, 1998, "Generalized impulse response analysis in linear multivariate models," *Economics Letters*, 58(1), 17–29.

Pesaran, M. H., 2015, *Time Series and Panel Data Econometrics*. Oxford University Press.

Platen, E., and M. Schweizer, 1998, "On feedback effects from hedging derivatives," *Mathematical Finance*, 8, 67–84.

Scholz, F. W., and M. A. Stephens, 1987, "K-Sample Anderson-Darling Tests," *Journal of the American Statistical Association*, 82(399), 918–924.

Sornette, D., F. Ulmann, and A. Wehrli, 2022, "On the Directional Destabilizing Feedback Effects of Option Hedging," Swiss Finance Institute Research Paper Series 22-34, Swiss Finance Institute.

Todorov, K., and G. Vilkov, 2024, "What could explain the recent drop in VIX?," BIS Quarterly Review, March 2024, Bank of International Settlements.

Vilkov, G., 2023, "0DTE Trading Rules," Working paper, Frankfurt School of Finance and Management.

Wiesen, T. F. P., and P. M. Beaumont, 2023, "A joint impulse response function for vector autoregressive models," *Empirical Economics*.

A Additional Tables

	Count	Mean	StDev	Min	25%	50%	75%	Max
0 DTE								
Trade Volume (USD, bn)	1447	192.7	204.7	4.1	40.4	89.7	304.5	854.4
Trade Volume Delta (USD, bn)	1447	47.0	49.5	1.3	11.9	23.4	71.4	227.1
Open Interest (USD, bn)	1447	163.6	113.4	11.3	78.7	132.8	216.8	849.3
Open Interest Delta (USD, bn)	1447	3.2	19.1	-135.4	-3.8	2.9	11.3	118.8
Open Interest Gamma (USD, bn)	1447	1376.0	906.4	7.0	712.6	1170.9	1773.5	7245.7
1 DTE								
Trade Volume (USD, bn)	1447	91.6	75.5	2.9	34.5	62.9	137.3	444.4
Trade Volume Delta (USD, bn)	1447	23.0	20.0	0.8	8.1	15.5	33.5	124.5
Open Interest (USD, bn)	1447	140.1	111.0	7.4	57.8	99.0	201.1	816.1
Open Interest Delta (USD, bn)	1447	3.0	18.3	-123.3	-2.8	2.2	8.9	146.8
Open Interest Gamma (USD, bn)	1447	1017.3	874.5	48.7	442.7	785.6	1337.1	16521.1
2-5 DTE								
Trade Volume (USD, bn)	2658	74.8	61.2	3.0	30.1	56.1	97.1	435.6
Trade Volume Delta (USD, bn)	2658	16.5	13.5	0.5	6.9	11.9	21.4	98.0
Open Interest (USD, bn)	2658	129.8	100.3	4.2	52.3	97.0	191.0	790.1
Open Interest Delta (USD, bn)	2658	2.8	16.9	-116.8	-3.1	2.0	8.2	145.2
Open Interest Gamma (USD, bn)	2658	862.2	668.2	28.0	364.9	686.6	1172.8	8020.8
6-10 DTE								
Trade Volume (USD, bn)	2756	33.4	22.0	0.8	16.9	28.9	45.6	167.8
Trade Volume Delta (USD, bn)	2756	7.6	5.2	0.1	3.8	6.3	10.4	36.8
Open Interest (USD, bn)	2756	89.7	82.3	3.9	26.7	58.9	130.8	645.5
Open Interest Delta (USD, bn)	2756	1.6	13.0	-99.6	-2.0	1.0	5.1	98.2
Open Interest Gamma (USD, bn)	2756	522.0	460.5	10.7	169.3	387.8	729.2	4607.8
11-22 DTE								
Trade Volume (USD, bn)	2801	36.5	24.7	0.6	16.8	32.5	50.6	148.9
Trade Volume Delta (USD, bn)	2801	8.7	6.1	0.1	4.1	7.4	11.8	43.9
Open Interest (USD, bn)	2801	74.2	76.2	0.6	16.1	46.1	108.8	601.9
Open Interest Delta (USD, bn)	2801	0.8	11.0	-107.6	-1.5	0.5	3.0	101.0
Open Interest Gamma (USD, bn)	2801	377.2	369.9	6.7	101.4	253.9	563.4	4333.3

Table A1: Volume and Open Interest by DTE Buckets. The table provides statistics for the selected open interest and volume variables defined in equations (3) to (5) for all options with roots SPY and SPXW aggregated by DTE buckets. The variables are first aggregated for each day: open interest variables use open interest in terms of number of contracts at the beginning of the day, and the underlying prices and option deltas and gammas reported at 10:00; trade volume variables are first computed for each 30-minute bar during the regular session from 9:30 to 16:00 using volume in contracts during each 30-minute interval, and underlying prices and deltas at the end of each bar, and then added up for each day. The sample period is from 01/2012 to 14/06/2023.

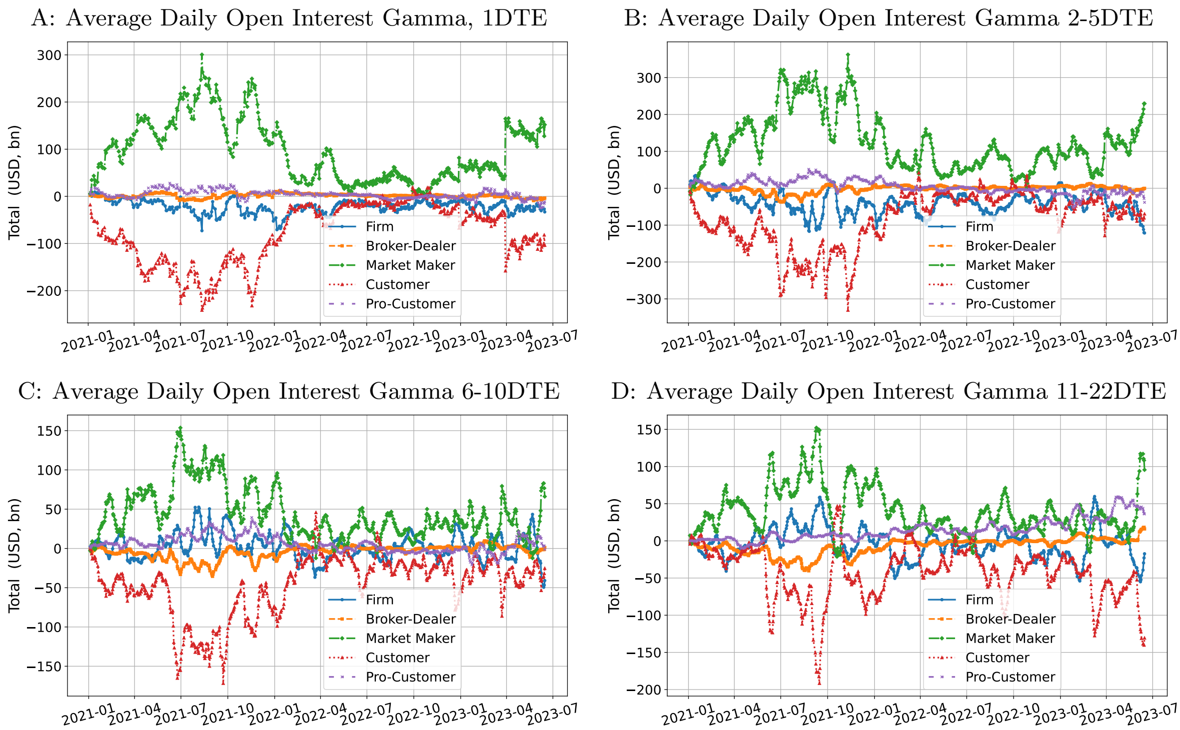

Figure A1: Open Interest Gamma by Trader Types and Days to Expiry. The figure shows the time series of the average intraday open interest dollar gamma $OI^{\$\Gamma}$ aggregated by trader types for different days to expiry buckets (from 1DTE in Panel A to 11-22DTE in Panel D). Open interest gammas are computed for SPXW options expiring on the day of trading. Series are smoothed using exponential moving average with halflife of five days. The sample period is from 01/2021 to 14/06/2023.

Online Appendix

for

0DTEs: Trading, Gamma Risk and Volatility Propagation

This version: August 1, 2024

IA.1 Robustness and Extensions

IA.1.1 Open Interest Gamma Effects

Intraday Market Maker Open Interest Speed and Charm Effects. In Section 4.1 we split the delta rebalancing needs into gamma, speed and charm components:

$$\Delta_{t_1} - \Delta_{t_0} \approx S \times \Gamma \times r_{t_0,t_1} + 0.5S^2 \times \frac{\partial^2 \Delta}{\partial S^2} \times r^2_{t_0,t_1} + \frac{\partial \Delta}{\partial t}(t_1 - t_0), \tag{IA.1.1}$$

where the first term quantifies the direct gamma effect, the second term quantifies the effect of gamma change, called "speed," and the third term quantifies delta time-decay, called "charm." For small time intervals it is customary to neglect second-order and time effects, and we also concentrate on the gamma effect in the main analysis. In dollar terms, by multiplying both sides of the equation above by underlying price, the excess portfolio delta to be offset through rebalancing can be approximated as follows:

$$\widehat{\$\Delta}_{t_1} \approx S^2 \times \Gamma \times r_{t_0,t_1} = \$\Gamma \times r_{t_0,t_1} + 0.5\$Speed \times r^2_{t_0,t_1} + \$Charm \times (t_1 - t_0), \tag{IA.1.2}$$

where we define dollar speed $\$Speed = S^3 \times \frac{\partial^2 \Delta}{\partial S^2}$ and dollar charm $\$Charm = S \times \frac{\partial \Delta}{\partial t}$.

Empirically, for the 01/2021 to 14/6/2023, for which we can compute the open interest of market makers, both dollar speed and charm are positive on average (and for most days), with charm being very small in magnitude (we compute it for a the 10-minute intraday interval). Being positive, both speed and charm will increase excess delta; in other words, they would increase selling pressure on the market, especially after large intraday return realizations (due to the $r^2_{t_0,t_1}$ term accompanying dollar speed). For large dollar speed and large negative return realizations, it can propagate intraday volatility in case market maker open interest gamma is small and overcompensated by the dollar speed term. We estimate a regression as in (9) in the main text, but with dollar speed and charm effects:

$$\begin{aligned} \ln RV^{day}_{t+1} = b_0 + & OI^{\$\Gamma}_{MM,t,0DTE} \times (b_1 + b_2\theta_t) + OI^{\$Speed}_{MM,t,0DTE} \times (b_3 + b_4\theta_t) \\ & + OI^{\$Charm}_{MM,t,0DTE} \times (b_5 + b_6\theta_t) + \mathbf{CX} + \varepsilon_z, \end{aligned} \tag{IA.1.3}$$

	$\ln RV_{t+1}$			
	(1)	(2)	(3)	(4)
$OI^{\$\Gamma}_{MM,t,0DTE}$	-0.584***	-0.427***	-0.472***	-0.444***
	(0.134)	(0.104)	(0.114)	(0.120)
$OI^{\$Speed}_{MM,t,0DTE}$	-0.017	-0.021	-0.006	-0.006
	(0.015)	(0.013)	(0.008)	(0.008)
$OI^{\$Charm}_{MM,t,0DTE}$	0.474***	0.374***	0.409***	0.391***
	(0.134)	(0.102)	(0.114)	(0.120)
$OI^{\$\Gamma}_{MM,t,0DTE} \times High\ RV_t$			0.060	
			(0.238)	
$OI^{\$Speed}_{MM,t,0DTE} \times High\ RV_t$			-0.083**	
			(0.039)	
$OI^{\$Charm}_{MM,t,0DTE} \times High\ RV_t$			-0.035	
			(0.232)	
$OI^{\$\Gamma}_{MM,t,0DTE} \times Neg\ Ret_t$				0.048
				(0.222)
$OI^{\$Speed}_{MM,t,0DTE} \times Neg\ Ret_t$				-0.034
				(0.026)
$OI^{\$Charm}_{MM,t,0DTE} \times Neg\ Ret_t$				-0.050
				(0.221)
$\ln RV_t$	0.558***	0.470***	0.409***	0.479***
	(0.017)	(0.019)	(0.025)	(0.025)
$\ln RV_{t-1}$	0.144***	0.144***	0.173***	0.126***
	(0.016)	(0.017)	(0.023)	(0.022)
$\ln RV_{t-2}$	-0.019	0.101***	0.104***	0.119***
	(0.012)	(0.014)	(0.020)	(0.018)
Ret_t	-0.166***	-0.212***	-0.560***	-0.047
	(0.035)	(0.038)	(0.091)	(0.074)
Ret_{t-1}	-0.037	-0.087***	0.083	-0.096***
	(0.025)	(0.027)	(0.067)	(0.032)
Ret_{t-2}	-0.017	-0.033	-0.161**	-0.053
	(0.024)	(0.024)	(0.069)	(0.034)
$High\ RV_t$			0.113***	
			(0.044)	
$Neg\ Ret_t$				-0.094**
				(0.043)
Year Dummies	No	Yes	Yes	Yes
Day of Week Dummies	No	Yes	Yes	Yes
Time of Dummies	No	Yes	Yes	Yes
R-squared Adj.	0.750	0.794	0.797	0.795
Obs.	4,920	4,920	4,920	4,920

Table IA.1: Conditional Effect of Market Maker Delta-Hedging. This table reports the results of a regression of log of intraday variance over 30-minutes, following every 30-minute time point, on the market maker SPXW 0DTE open interest gamma, speed and charm, denoted $OI^{\$\Gamma}_{MM,t,0DTE}$, $OI^{\$Speed}_{MM,t,0DTE}$, and $OI^{\$Charm}_{MM,t,0DTE}$. Each variable is interacted with a dummy variable indicating negative last 30-minute return of the index ($Neg\ Ret_t$) or high (above its sample median) last 30-minute variance of the index ($High\ RV_t$). The dependent variable and all continuous independent variables before interaction are standardized to unit variance. The regression controls for three lags of the dependent variable and of the returns computed over the same intervals as the lags of the dependent variable. All the continuous controls are interacted with $Neg\ Ret_t$ and $High\ RV_t$, but their coefficients are suppressed for brevity. Standard errors are based on Newey and West (1987) with five lags. The sample period is from 01/2021 to 14/06/2023.

where θ_t is one of the dummy variables—$High\ RV_t$ indicating past realized 30-minute variance above its sample median, and $Neg\ Ret_t$ indicating negative last 30-minute return of the underlying index. The results in Table IA.1 indicate that, on average, the dollar speed has an insignificant effect on the future variance, while charm coefficient is positive and significant, always increasing variance for its positive values. What matters most, however, is that all interactions with a negative return dummy are insignificant, so that neither of the excess open interest delta components contribute to the "bad" variance propagation. Interaction of speed with high variance dummy is even negative with borderline significance, thus linked to lower future variance when variance is high at the moment.

Intraday Market Maker Open Interest Gamma Effects: Variance Period Variations. To test the sensitivity of the results for the intraday market maker's open interest gamma effects on intraday variance, reported in Tables 2 and 3, we vary the period for intraday variance computation. In Tables IA.2 and IA.3 we report the results of the regressions using 10-minute intraday variances instead of the 30-minute variances in the main analysis, stressing this way a more short-term gamma effect. A few coefficients change slightly, but the magnitude and significance of the main effects are similar, leading us to the same conclusions as in the main text. The only significant change happens to the negative gamma effect in Table IA.3—it is still positive, but loses significance: The total effects are 0.012 and 0.034 in columns (1) and (2), with t-stats of 0.37 and 1.14, respectively. When market makers are net short in 0DTEs, their open interest does not significantly affects the subsequent short-term realized variance.

Start of Day Aggregate Open Interest Gamma Effects: Variance Period Variations. We also test sensitivity of the results reported in Table 5, in which we regress intraday log variance on the start-of-day open interest gamma and its interactions with overnight and lagged daily variances. Instead of using full day variance as dependent variable we compute intraday variance from 10:00 (point, at which we evaluate gamma of the start of day open interest) to 14:00 or 12:00. Table IA.4 reports the numbers for the variance between 10:00 and 14:00, and the results are very similar to the ones reported in the main text.

	$\ln RV_{t+1}$						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$OI^{\$\Gamma}_{MM,t,0DTE}$	-0.095***	-0.065***					-0.057***
	(0.009)	(0.009)					(0.010)
$OI^{\$\Gamma}_{MM,t,1DTE}$			-0.068***				-0.057***
			(0.011)				(0.014)
$OI^{\$\Gamma}_{MM,t,2-5DTE}$				-0.065***			-0.057***
				(0.008)			(0.011)
$OI^{\$\Gamma}_{MM,t,6-10DTE}$					-0.039***		-0.029***
					(0.007)		(0.010)
$OI^{\$\Gamma}_{MM,t,11-22DTE}$						-0.028***	0.004
						(0.006)	(0.009)
$\ln RV_t$	0.289***	0.278***	0.277***	0.285***	0.291***	0.291***	0.245***
	(0.015)	(0.014)	(0.014)	(0.013)	(0.013)	(0.013)	(0.017)
$\ln RV_{t-1}$	0.296***	0.277***	0.272***	0.275***	0.282***	0.283***	0.256***
	(0.015)	(0.015)	(0.015)	(0.013)	(0.013)	(0.013)	(0.018)
$\ln RV_{t-2}$	0.241***	0.248***	0.263***	0.255***	0.260***	0.263***	0.238***
	(0.014)	(0.014)	(0.014)	(0.013)	(0.013)	(0.013)	(0.017)
Ret_t	-0.038***	-0.041***	-0.045***	-0.048***	-0.047***	-0.048***	-0.036***
	(0.007)	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.008)
Ret_{t-1}	-0.031***	-0.030***	-0.029***	-0.031***	-0.030***	-0.031***	-0.028***
	(0.007)	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.008)
Ret_{t-2}	-0.006	-0.010	-0.013*	-0.011*	-0.009	-0.010	-0.015*
	(0.007)	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.009)
Year Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
Day of Week Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
Time Dummies	No	Yes	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.685	0.704	0.708	0.717	0.716	0.715	0.683
Obs.	5,894	5,894	5,894	7,382	7,382	7,382	4,406

Table IA.2: Market Maker Open Interest Gamma and Underlying Variance. This table reports the results of a regression of log of intraday variance over the 10-minute interval, following every 30-minute intraday time point, on the market maker open interest dollar gamma in SPXW options for different DTEs, denoted $OI^{\$\Gamma}_{MM,t,nDTE}$. The dependent variable and all continuous independent variables are standardized to unit variance. The regression controls for three lags of dependent variable and of the returns for the same intervals. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2021 to 14/06/2023.

IA.1.2 Daily 0DTE Trading Volume Effects

To understand why our finding of no apparent propagation of the underlying index volatility through the 0DTEs market differs from the positive effect of 0DTE trading volume on the underlying variance documented in Brogaard, Han, and Won (2023), we note that our approaches are very different. While Brogaard, Han, and Won directly relate daily variance to the 0DTE volume, we estimate intraday propagation of shocks in a system with absolute normalized returns and trading volumes in 0DTEs and underlying, respectively, and only then relate the intensity of shock propagation to 0DTE volume and other variables. Moreover, in other tests, we focus

	$\ln RV_{t+1}$					
	(1)	(2)	(3)	(4)	(5)	(6)
$OI^{\$\Gamma}_{MM,t,0DTE}$	-0.109***	-0.086***	-0.105***	-0.075***	-0.103***	-0.071***
	(0.013)	(0.012)	(0.011)	(0.010)	(0.012)	(0.011)
$OI^{\$\Gamma}_{MM,t,0DTE} \times Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$	0.116***	0.114***				
	(0.034)	(0.032)				
$OI^{\$\Gamma}_{MM,t,0DTE} \times High\ RV_t$			0.024	0.032*		
			(0.019)	(0.019)		
$OI^{\$\Gamma}_{MM,t,0DTE} \times Neg\ Ret_t$					0.019	0.017
					(0.017)	(0.016)
$\ln RV_t$	0.295***	0.284***	0.274***	0.253***	0.326***	0.315***
	(0.017)	(0.017)	(0.025)	(0.024)	(0.024)	(0.023)
$\ln RV_{t-1}$	0.280***	0.259***	0.286***	0.274***	0.276***	0.264***
	(0.018)	(0.018)	(0.022)	(0.021)	(0.022)	(0.021)
$\ln RV_{t-2}$	0.242***	0.248***	0.247***	0.254***	0.238***	0.245***
	(0.016)	(0.016)	(0.020)	(0.020)	(0.021)	(0.020)
Ret_t	-0.052***	-0.055***	-0.112***	-0.120***	-0.053***	-0.058***
	(0.009)	(0.009)	(0.023)	(0.022)	(0.018)	(0.017)
Ret_{t-1}	-0.030***	-0.032***	-0.075***	-0.067***	-0.046***	-0.045***
	(0.009)	(0.009)	(0.018)	(0.017)	(0.009)	(0.009)
Ret_{t-2}	-0.011	-0.017**	0.009	0.007	-0.011	-0.019*
	(0.009)	(0.009)	(0.020)	(0.019)	(0.010)	(0.010)
$Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$	0.039	0.043				
	(0.042)	(0.042)				
$High\ RV_t$			0.084	0.092		
			(0.070)	(0.070)		
$Neg\ Ret_t$					-0.055	-0.084
					(0.058)	(0.057)
Year Dummies	No	Yes	No	Yes	No	Yes
Day of Week Dummies	No	Yes	No	Yes	No	Yes
Time Dummies	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.686	0.705	0.686	0.705	0.686	0.705
Obs.	5,894	5,894	5,894	5,894	5,894	5,894

Table IA.3: Conditional Effect of Market Maker Open Interest Gamma on Underlying Variance. This table reports the results of a regression of log of intraday variance over the 10-minute interval, following every 30-minute time point on the market maker SPXW 0DTE open interest dollar gamma($OI^{\$\Gamma}_{MM,t,0DTE}$), and its interaction with dummy variables indicating negative last 10-minute index return ($Neg\ Ret_t$), last 10-minute variance of the underlying index above its sample median ($High\ RV_t$), and negative open interest gamma ($Neg\ OI^{\$\Gamma}_{MM,t,0DTE}$). The dependent variable and all continuous independent variables before interaction are standardized to unit variance for interpretability. The regression controls for three lags of the dependent variable and 10-minute realized returns over the same intervals. All control variables are interacted with conditioning dummies, but their coefficient are suppressed for brevity. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2021 to 14/06/2023.

on whether the potential delta-hedging intensity captured by 0DTE gamma, instead of 0DTE trading volume, propagates recently realized underlying variance and find that it does not.

We dig deeper into the sources of the somewhat conflicting findings using a specification similar to Brogaard, Han, and Won's baseline result. We regress day d intraday variance RV_d of the SPX index on the morning open interest dollar gamma $OI^{\$\Gamma}_d$, lagged 0DTE volume, for which we use either log of 0DTE dollar volume (with and without delta adjustment), denoted $0DTE\ Volume_{d-1}$, or the proportion of 0DTE dollar trading volume relative to that of all

	0-DTE	1-DTE	$\ln RV_d^{day}$ 2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV_d^{on}$	-0.011	-0.047**	-0.008	-0.030**	-0.037**
	(0.015)	(0.019)	(0.014)	(0.014)	(0.017)
$OI^{\$\Gamma}_{dte,d} \times \ln RV_{d-1}^{day}$	0.000	-0.002	-0.031**	-0.032**	-0.007
	(0.018)	(0.017)	(0.013)	(0.012)	(0.013)
$OI^{\$\Gamma}_{dte,d}$	-0.097	-0.262	-0.466***	-0.573***	-0.285**
	(0.185)	(0.162)	(0.139)	(0.132)	(0.137)
$\ln RV_d^{on}$	0.088***	0.083***	0.074***	0.103***	0.115***
	(0.030)	(0.031)	(0.022)	(0.022)	(0.026)
$\ln RV_{d-1}^{day}$	0.540***	0.566***	0.590***	0.602***	0.577***
	(0.038)	(0.037)	(0.029)	(0.027)	(0.028)
$\ln RV_{d-2}^{day}$	0.152***	0.186***	0.129***	0.141***	0.143***
	(0.031)	(0.032)	(0.023)	(0.023)	(0.023)
$\ln RV_{d-3}^{day}$	0.046	-0.006	0.024	0.016	0.019
	(0.033)	(0.030)	(0.022)	(0.022)	(0.022)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.751	0.749	0.738	0.734	0.729
Obs.	1,447	1,447	2,661	2,769	2,801

Table IA.4: Volatility Propagation by Open Interest Gamma. This table reports the results of a regression of log of intraday variance computed from 1-minute log returns between 10:00 and 14:00 on the level of overnight variance and lagged intraday variance both interacted with start-of-day open interest dollar gamma by DTE buckets, using the specification in (10). Start-of-day open interest is converted to dollar gamma $OI^{\$\Gamma}_{d:sod,dte}$ at 10:00 each day and aggregated for SPY and SPXW options with moneyness levels in $[0.5, 1.5]$ for each DTE bucket. Realized variances are computed from intraday and overnight returns for SPX index. Dependent and independent variables before interaction are standardized to unit variance. Five lags of dependent variable are included, but only two are shown for brevity. Standard errors in parentheses use Newey and West (1987) with five lags. The sample period is from 01/2012 to 14/06/2023.

options for the same underlying maturing within the next month, denoted $DTE0\%$.[19] Because trading volumes and daily variances can be persistent, we estimate the specification with and without the following controls: lagged values of the dependent variable, which accounts for the persistence of the outcome, and year-fixed effects to account for common trends. The results provided in Table IA.6 are consistent with our inferences after accounting for the above-mentioned controls.

IA.1.3 VAR Analysis Extensions

Impulse Response Functions Dynamics. In the main text we made an informal statistical inference about the significance of the impulse response intensity time dynamics based on the overlap of the confidence bounds. To see whether the propagation of the shocks to volatility and both 0DTE and underlying trading volumes is related to 0DTE trading activity, we relate each

[19] As in the main part of the paper, we use options with roots SPXW and SPY, i.e., do not include regular SPX options with AM settlement.

	$\ln RV_d^{day}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
Panel A: Early Period, 2012-2019					
$OI_{dte,d}^{\$\Gamma} \times \ln RV_d^{on}$	0.000	-0.049	-0.016	-0.036**	-0.039**
	(0.021)	(0.032)	(0.016)	(0.018)	(0.019)
$OI_{dte,d}^{\$\Gamma} \times \ln RV_{d-1}^{day}$	-0.029	0.031	-0.015	-0.012	0.005
	(0.024)	(0.028)	(0.016)	(0.017)	(0.017)
$OI_{dte,d}^{\$\Gamma}$	-0.365	0.113	-0.350**	-0.402**	-0.136
	(0.236)	(0.280)	(0.175)	(0.198)	(0.194)
$\ln RV_d^{on}$	0.047	0.072	0.071***	0.090***	0.097***
	(0.037)	(0.047)	(0.024)	(0.026)	(0.027)
$\ln RV_{d-1}^{day}$	0.608***	0.524***	0.564***	0.566***	0.553***
	(0.053)	(0.055)	(0.036)	(0.037)	(0.038)
$\ln RV_{d-2}^{day}$	0.044	0.153***	0.081***	0.098***	0.104***
	(0.042)	(0.049)	(0.029)	(0.030)	(0.030)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.641	0.674	0.643	0.638	0.633
Obs.	793	792	1,790	1,898	1,930
Panel B: Recent Period, 2020-2023					
$OI_{dte,d}^{\$\Gamma} \times \ln RV_d^{on}$	-0.019	-0.013	0.003	-0.015	-0.050**
	(0.021)	(0.019)	(0.024)	(0.021)	(0.021)
$OI_{dte,d}^{\$\Gamma} \times \ln RV_{d-1}^{day}$	0.018	-0.031	-0.044*	-0.054***	0.003
	(0.026)	(0.021)	(0.024)	(0.021)	(0.021)
$OI_{dte,d}^{\$\Gamma}$	0.021	-0.420*	-0.481**	-0.664***	-0.216
	(0.267)	(0.223)	(0.234)	(0.206)	(0.194)
$\ln RV_d^{on}$	0.094**	0.048	0.044	0.081*	0.166***
	(0.045)	(0.036)	(0.050)	(0.047)	(0.054)
$\ln RV_{d-1}^{day}$	0.490***	0.575***	0.592***	0.621***	0.522***
	(0.053)	(0.045)	(0.053)	(0.052)	(0.055)
$\ln RV_{d-2}^{day}$	0.210***	0.210***	0.203***	0.204***	0.208***
	(0.042)	(0.041)	(0.039)	(0.037)	(0.038)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.709	0.713	0.712	0.715	0.712
Obs.	654	655	871	871	871

Table IA.5: Aggregate Open Interest Gamma Effects for Subperiods. This table reports the results of a regression of log of intraday variance on the level of overnight variance and lagged intraday variance both interacted with open interest dollar gamma at market open by DTE buckets, using the specification in (10). Open interest is recorded at market open and converted to dollar gamma $OI_{d,dte}^{\$\Gamma}$ using underlying prices and option gamma levels at 10:00 each day. Dollar gammas are aggregated for SPY and SPXW options with moneyness levels in $[0.5, 1.5]$ for each DTE bucket. Realized variances are computed from intraday and overnight returns for SPX index. All continuous variables before interaction are standardized to unit variance. Five lags of daily variance ($\ln RV^{day}$) are used, but only two are shown for brevity. Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 12/2019 in Panel A and 01/2020 to 14/06/2023 in Panel B.

day's cumulative generalized impulse response after five time steps (i.e., five minutes for the 1-minute VAR frequency) to year dummies, overnight and intraday variances, and to dummy

	Using $Vol^{\$}$				Using $Vol^{\$\Delta}$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A. 0DTE Volume as Explanatory Variable								
$OI^{\$\Gamma}_{d-1}$	-0.244***	-0.204***	-0.014	-0.012	-0.253***	-0.215***	-0.016	-0.016
	(0.064)	(0.052)	(0.013)	(0.016)	(0.065)	(0.056)	(0.014)	(0.017)
$0DTE\ Volume_{d-1}$	0.269***	0.434***	0.027	0.054	0.267***	0.386***	0.029	0.061
	(0.036)	(0.087)	(0.020)	(0.059)	(0.036)	(0.085)	(0.020)	(0.056)
RV^{day}_{d-1}			0.487***	0.485***			0.487***	0.484***
			(0.151)	(0.152)			(0.151)	(0.151)
RV^{day}_{d-2}			0.489***	0.482***			0.489***	0.482***
			(0.158)	(0.157)			(0.158)	(0.157)
RV^{day}_{d-3}			0.076	0.079			0.076	0.079
			(0.100)	(0.100)			(0.100)	(0.100)
RV^{day}_{d-4}			-0.032	-0.035			-0.031	-0.035
			(0.072)	(0.071)			(0.072)	(0.071)
RV^{day}_{d-5}			-0.096	-0.098			-0.096	-0.098
			(0.069)	(0.069)			(0.069)	(0.069)
Year Dummies	No	Yes	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.076	0.133	0.724	0.724	0.074	0.133	0.724	0.724
Obs.	1,445	1,445	1,444	1,444	1,445	1,445	1,444	1,444
Panel B. 0DTE% as Explanatory Variable								
$OI^{\$\Gamma}_{d-1}$	-0.212***	-0.152***	-0.009	-0.001	-0.221***	-0.130***	-0.007	0.008
	(0.061)	(0.044)	(0.011)	(0.011)	(0.059)	(0.038)	(0.012)	(0.013)
$0DTE\ Volume_{d-1}$	0.196***	-0.016	0.010	-0.036	0.128***	-0.078	-0.001	-0.045*
	(0.030)	(0.055)	(0.017)	(0.025)	(0.022)	(0.063)	(0.015)	(0.023)
RV^{day}_{d-1}			0.491***	0.489***			0.492***	0.487***
			(0.150)	(0.150)			(0.150)	(0.150)
RV^{day}_{d-2}			0.490***	0.483***			0.491***	0.482***
			(0.158)	(0.157)			(0.158)	(0.157)
RV^{day}_{d-3}			0.074	0.077			0.074	0.079
			(0.099)	(0.099)			(0.098)	(0.099)
RV^{day}_{d-4}			-0.029	-0.035			-0.028	-0.035
			(0.072)	(0.071)			(0.072)	(0.071)
RV^{day}_{d-5}			-0.096	-0.100			-0.096	-0.100
			(0.069)	(0.069)			(0.069)	(0.069)
Year Dummies	No	Yes	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.053	0.122	0.724	0.724	0.036	0.123	0.724	0.724
Obs.	1,445	1,445	1,444	1,444	1,445	1,445	1,444	1,444

Table IA.6: Daily Realized Variance vs. 0DTE Trading Volume. This table reports the results of a daily time series regression of intraday variance of the SPX index on the lagged values of open interest dollar gamma $OI^{\$\Gamma}_{d-1}$ and the lagged 0DTE volume proxy, computed from either dollar or dollar delta volume, as indicated in the Table headers. In Panel A, $0DTE\ Volume_{d-1}$ is the log of the volume variable indicated in the Table header. In Panel B, $0DTE\%_{d-1}$ is the proportion of 0DTE trading volume indicated in the Table header relative to the total of the corresponding trading volume of all options (SPY and SPXW) expiring within the next month. As additional controls, we use lagged intraday variances and year fixed effects. All continuous variables are standardized to unit variance. Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

variables for considerable (more than one standard deviation) jumps of open interest dollar gamma and 0DTEs trading volume relative their past averages.[20] Table IA.7 shows the results

[20]Both standard deviation and averages are computed from the past 21 daily observations.

Impulse	Variance			0DTE Volume			Underlying Volume		
Propagation	Variance	0DTE Vol.	Und.Vol.	Variance	0DTE Vol.	Und.Vol.	Variance	0DTE Vol.	Und.Vol.
$High\ OI_d^{\$\Gamma}$	-0.000	-0.005	-0.008	-0.001	0.007	-0.003	-0.042	-0.000	0.001
	(0.032)	(0.006)	(0.008)	(0.020)	(0.008)	(0.008)	(0.031)	(0.010)	(0.007)
$High\ \ln Vol_d^{\$\Delta}$	0.021	0.009*	0.009	0.010	0.015***	0.004	-0.001	0.003	0.008
	(0.023)	(0.005)	(0.006)	(0.016)	(0.006)	(0.006)	(0.020)	(0.007)	(0.005)
$\ln RV_d^{on}$	-0.022***	-0.004***	-0.004***	-0.006*	-0.000	-0.004**	-0.019***	-0.005***	-0.004***
	(0.005)	(0.001)	(0.002)	(0.004)	(0.001)	(0.002)	(0.005)	(0.001)	(0.001)
$\ln RV_d^{day}$	0.008	0.009***	0.006**	-0.000	0.001	-0.003	0.000	0.003	-0.002
	(0.009)	(0.002)	(0.002)	(0.006)	(0.002)	(0.002)	(0.008)	(0.002)	(0.002)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dep. Lags	5	5	5	5	5	5	5	5	5
R-squared Adj.	0.043	0.076	0.023	0.284	0.106	0.343	0.075	0.401	0.067
Obs.	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421

Table IA.7: Conditional Generalized Impulse Response Functions. This table reports the analysis of the 5-step cumulative responses based on the cumulative gIRFs from the VAR system (11) estimated daily using 1-minute data for Variance, 0DTE Volume (0DTE Vol., in dollar delta terms), and Underlying Volume (Und.Vol., in dollar terms). We regress the cumulative gIRFs on its five lags, log of overnight variance ($\ln RV_d^{on}$), log of intraday variance ($\ln RV_d^{day}$), and dummy variables $High\ OI_d^{\$\Gamma}$ and $High\ \ln Vol_d^{\$\Delta}$, equal one for large positive deviations of day d values from their rolling-window averages. Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

of the regressions. Neither high open interest gamma ($High\ OI_{dte,d}^{\$\Gamma}$) nor high 0DTE trading volume ($High\ \ln Vol_d^{\$\Delta}$) is linked to significantly higher responses to shocks in the system, except for one case, where the propagation of 0DTE volume to the underlying market volume is significantly larger when 0DTE volume is high relative to its recent past average. In Table IA.8, we include interactions of gamma and volume variables with year dummies, respectively, and do not find a significantly stronger association between high open interest and trading volume and the propagation 0DTE Volume shocks in more recent periods. Running the same regression only with year-fixed effects barely reduces the explanatory power of the model, and we observe a strong time trend in the last 3-4 years, with shocks to 0DTE trading volume propagating significantly stronger to all other variables in the system.[21]

VAR Analysis for Other DTE Buckets. To see whether the time trend in impulse response intensity is specific to the 0DTEs, we re-estimate the VAR system in (11) using option volume variable for other maturity buckets, and also for the volume aggregated over all maturities up to 22 trading days. Figure IA.1 shows the time-series plots of the smoothed cumulative responses five steps after a shock. In Panel A, we observe a stronger response of volatility to short-term

[21]The pattern of the year effects looks very similar to the trend in the 0DTE trading volume documented in Figure 2. Hence, directly including the (non-stationary and trending) volume variable in our regression would lead to spurious results. Using dummies for high gamma and volume mitigates the problem.

Impulse	Variance			0DTE Volume			Underlying Volume		
Propagation	Variance	0DTE Vol.	Und.Vol.	Variance	0DTE Vol.	Und.Vol.	Variance	0DTE Vol.	Und.Vol.
$High\ OI_d^{\$\Gamma}$	-0.016	-0.001	-0.005	-0.014	0.004	-0.003	-0.030	0.003	0.001
	(0.022)	(0.004)	(0.006)	(0.013)	(0.006)	(0.005)	(0.022)	(0.007)	(0.006)
$High\ \ln Vol_d^{\$\Delta}$	0.098***	0.005	-0.001	-0.041***	0.022***	-0.017***	-0.014	-0.016***	0.016***
	(0.020)	(0.004)	(0.004)	(0.011)	(0.005)	(0.006)	(0.018)	(0.005)	(0.004)
$\ln RV_d^{on}$	-0.022***	-0.004***	-0.004***	-0.006*	-0.001	-0.004**	-0.019***	-0.005***	-0.004***
	(0.005)	(0.001)	(0.002)	(0.004)	(0.001)	(0.002)	(0.005)	(0.001)	(0.001)
$\ln RV_d^{day}$	0.010	0.009***	0.006***	0.000	0.002	-0.003	0.001	0.003*	-0.002
	(0.009)	(0.002)	(0.002)	(0.006)	(0.002)	(0.002)	(0.008)	(0.002)	(0.002)
$High\ OI_d^{\$\Gamma} \times Year$ 2013	-0.000***	-0.000***	-0.000***	-0.000	0.000***	-0.000**	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2014	-0.000***	0.000***	-0.000	0.000*	0.000	-0.000	-0.000***	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2015	-0.000	0.000	-0.000	-0.000	-0.000***	-0.000**	-0.000*	-0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2016	0.000***	0.000	0.000	0.000	0.000	0.000**	0.000**	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2017	0.000	0.000	0.000**	0.000	-0.000	0.000***	-0.000*	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2018	0.000	0.000	-0.000	0.000	-0.000	-0.000***	-0.000	-0.000*	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2019	0.000**	-0.000**	0.000**	-0.000	-0.000***	0.000	-0.000*	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2020	0.000**	-0.000	0.000	-0.000	0.000	0.000	-0.000	0.000***	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2021	0.000	-0.000	-0.000	0.000	0.000	-0.000	-0.000**	0.000	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ OI_d^{\$\Gamma} \times Year$ 2022	0.038	-0.007	-0.003	0.000	0.005	0.005	-0.015	0.009	0.001
	(0.031)	(0.006)	(0.009)	(0.021)	(0.009)	(0.010)	(0.037)	(0.011)	(0.009)
$High\ OI_d^{\$\Gamma} \times Year$ 2023	-0.054	0.006	-0.002	-0.014	-0.001	-0.008	-0.015	-0.005	-0.000
	(0.038)	(0.007)	(0.011)	(0.021)	(0.008)	(0.008)	(0.033)	(0.010)	(0.009)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2013	0.007	-0.004	0.002	0.006	0.003	0.000	-0.018	-0.000	-0.011***
	(0.021)	(0.004)	(0.003)	(0.008)	(0.005)	(0.005)	(0.016)	(0.004)	(0.004)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2014	-0.013	-0.004	-0.001	0.001	-0.003	0.000	-0.012	-0.001	-0.002
	(0.017)	(0.004)	(0.003)	(0.009)	(0.005)	(0.005)	(0.014)	(0.004)	(0.005)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2015	-0.037**	-0.005	-0.001	0.014	-0.008**	0.000	0.004	0.001	-0.007**
	(0.017)	(0.003)	(0.004)	(0.010)	(0.004)	(0.005)	(0.016)	(0.004)	(0.003)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2016	-0.122***	0.006	0.007	0.008	-0.013*	0.022**	0.017	0.023**	-0.008
	(0.036)	(0.007)	(0.007)	(0.023)	(0.007)	(0.010)	(0.028)	(0.010)	(0.008)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2018	-0.310***	-0.033***	-0.048***	0.008	-0.016*	-0.023**	-0.184***	0.017**	-0.031***
	(0.039)	(0.007)	(0.008)	(0.022)	(0.008)	(0.009)	(0.033)	(0.008)	(0.008)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2020	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2021	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2022	-0.046	-0.005	0.008	0.108***	-0.011	0.021	0.027	-0.008	-0.010
	(0.040)	(0.009)	(0.011)	(0.029)	(0.012)	(0.014)	(0.044)	(0.014)	(0.012)
$High\ \ln Vol_d^{\$\Delta} \times Year$ 2023	-0.037	0.015	0.018	0.060*	0.006	0.018	0.002	0.038***	-0.003
	(0.047)	(0.011)	(0.013)	(0.031)	(0.014)	(0.011)	(0.045)	(0.013)	(0.010)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dep. Lags	5	5	5	5	5	5	5	5	5
R-squared Adj.	0.045	0.076	0.021	0.286	0.104	0.342	0.073	0.402	0.064
Obs.	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421

Table IA.8: Conditional gIRFs with Year Interactions. This table reports the results of a regression of cumulative generalized impulse responses after five time steps, estimated on days with 0DTE expiration for VAR system (11) at 1-minute frequency. Compared to the main-text table, current table additionally includes interaction of year effects with dummies $High\ OI_{dte,d}^{\$\Gamma}$ and $High\ \ln Vol_d^{\$\Delta}$ taking value of one for large positive deviations of day d values from the respective rolling-window average. Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

options' trading volume for all years, and its very pronounced upward trend starting around the second quarter of 2020, led by 0- and 1DTEs. Options with more than a week to expiration have a stable or even a slightly decreasing (for 11-22DTEs) cumulative response. The responses are also sizeable, reaching almost 0.4 of the standard deviation. Realized return (volatility) shocks also propagate stronger to short-term options, but with a negligible size of the cumulative effect. Option and underlying trading look very similar, with a relatively sizeable shock propagation in both directions, with an increasing trend for the short-term options. Notably, the effects (in both directions) for the *aggregate* options volume seems to be almost completely driven by ultra-short-term buckets. A possible explanation for the observed time effects is an increasing

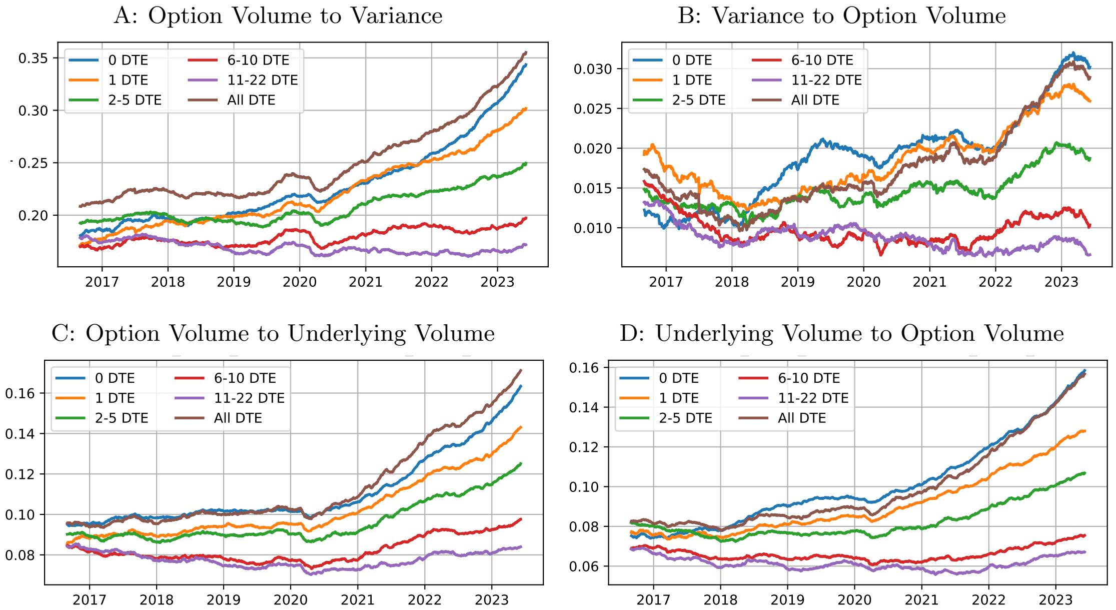

Figure IA.1: Dynamics of Option Volume and Variance Cumulative gIRFs. The figure shows the smoothed (exponential moving average with half life of 252 days) time-series of the cumulative generalized impulse response functions after 5 steps for the VAR system in (11) estimated each day for 1-minute frequency with $n = 5$ lags, separately for option volume in different maturity buckets. The variables are normalized daily to unit variance, and the response is calculated for one-standard-deviation shock to a given variable. The sample period is from 01/2012 to 14/06/2023.

integration of the underlying and option markets for liquid contracts (e.g., Dew-Becker and Giglio 2023), which is consistent with the increased correlation between trading volumes (from relatively uniform annual average levels of 0.25-0.3 before 2021 to 0.38, 0.44, and 0.59 in the next three years, respectively). At the same time, trading in both 0DTE and underlying markets became much smoother over the years, with the average daily standard deviation of intraday log volume differences dropping from 1.49 in 2012 to 0.49 in 2023 for 0DTEs, and from 0.80 to 0.47 for the underlying instruments.

IA.1.4 Variance Risk Premium and Option Returns

We use EOD closing prices of SPX and SPY at 16:00 to compute the final payoff for the available options (we assume that payoff on options with physical exercise can be approximated by the cash settlement at the day close) according to its type.

To compute the implied variance (IV) to expiration at the end of each available bar for each underlying j we use VIX Cboe (2023) methodology applied to SPX options for a given trading days to expiration (dte) observed at the end of a bar $d:t$, with the difference that we estimate variance for one particular maturity without interpolation in time dimension to match 30 days to maturity and we do not scale it to annual terms:

$$IV_{j,dte,d:t} = 2e^{rT} \sum_i \frac{\Delta K_i}{K_i^2} Q(K_i) - [F/K_0 - 1]^2, \quad \text{(IA.1.4)}$$

where K_i is the strike price of out-the-money (OTM) call and put options, K_0 is the first strike equal to or otherwise immediately below current option-implied forward price F, $Q(K_i),\ i \neq 0$, is the mid-quote of OTM call and put options, and $Q(K_0)$ is the average of the K_0 put option price and K_0 call option price, r is the risk-free rate, for which we use 1-month T-bill rate from FRED, and T is time to expiration (in years).

We define *ex post* realized variance risk premium VRP to expiration at a given bar $d:t$ and dte as the difference in the respective implied and realized variances from the end of a given intraday bar until expiration date and time:

$$VRP_{j,dte,d:t} = IV_{j,dte,d:t} - RV_{j,dte,d:t}. \quad \text{(IA.1.5)}$$

We can annualize IV, RV, and VRP by dividing each by time to expiration (in minutes) and multiplying by the number of minutes in a year ($365 \times 24 \times 60$). Using the (non-annualized) VRP to expiration, we also define and compute intermediate variance risk premium realized over time interval Δt up to time bar $d:t$:

$$VRP^{\Delta}_{j,dte,d:t,\Delta t} = VRP_{j,dte,d:t-\Delta t} - VRP_{j,dte,d:t}, \tag{IA.1.6}$$

and we can scale it up to annual terms by a factor $365 \times 24 \times 60/\Delta t$.

0DTE options are gaining popularity among investors, and the dynamics of their trading volume documented above speaks for itself. To ascertain the special features of 0DTEs, we first look at the average variance risk premium priced into these options and compare it to the other DTE buckets. First, at the end of each bar during a trading day, we compute the annualized VRP defined in equation (IA.1.5) for each available maturity within the next 22 trading days and then average all computed VRPs by DTE buckets for each year in the sample.[22] The

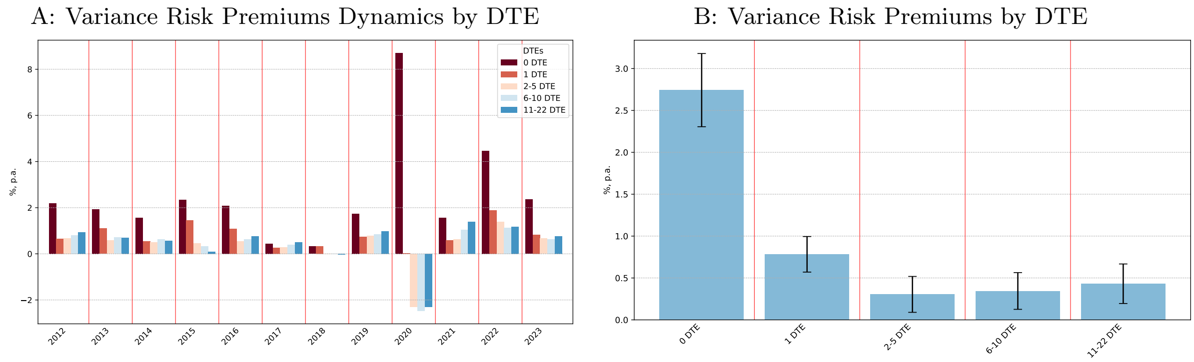

Figure IA.2: Variance Risk Premiums. The figure shows average variance risk premiums (VRP) for SPXW options by DTE buckets and years (Panel A) and by DTE buckets (Panel B). VRP is computed as implied minus realized variances to expiration at 16:00 annualized using exact minutes to expiration and $365 \times 24 \times 60$ minutes per day. In Panel A we average ex-post realized VRPs for a given DTE bucket at 10:00 ET for all days each year. In Panel B we average the same VRPs by DTE buckets for the whole sample (95% confidence bounds based on Newey and West (1987) standard errors with 10 lags). The sample period is from 01/2012 to 14/06/2023.

average VRPs by DTE buckets and years shown in Figure IA.2, Panel A, clearly demonstrate the distinction between 0DTEs and *all other* maturities: zero-day-to-expiration options are far more expensive than the others, attaining highly positive values even in 2020 when all other expiration buckets turned negative due to extremely high realized volatility during the COVID crisis. Interestingly, other maturities do not demonstrate a uniform term structure over the years, e.g., increasing in 2021 and being flat in 2022. In Panel B, we observe also that the

[22] We use only SPXW root for VRP and option return computations because the integrated implied variance formulas as in (IA.1.4) assume European options and cash settlement of index options make subsequent option return computations more transparent.

realized VRP to maturity has a U-shape, i.e., it is extremely high for 0DTEs, then goes down for VRPs up to a week to expiry, and then goes up, but at a very slow pace.

A high realized variance risk premium is either rational, i.e., can be justified by higher risks of ultra-short-term options, or irrational, not stemming from higher risks on investment but rather from forces like sentiment or market microstructure factors. However, it seems intuitive that 0DTE options are riskier than the longer-term ones given that option risk tends to increase closer to expiration time: (i) they are cheaper for a unit of directional bet and provide higher leverage; (ii) they have higher gamma risk, which increases exponentially closer to expiration for near at-the-money options; (iii) they are exposed to pin risk; and (iv) they experience an increasing time decay closer to expiration. Figure IA.3 shows average annualized VRPs until expiration time (16:00) computed at the end of each 30-minute bar during the day. The risk premium is clearly increasing during the day, and sharply so in the last several bars before the expiration.

A: 0DTEs Variance Risk Premiums to Expiration

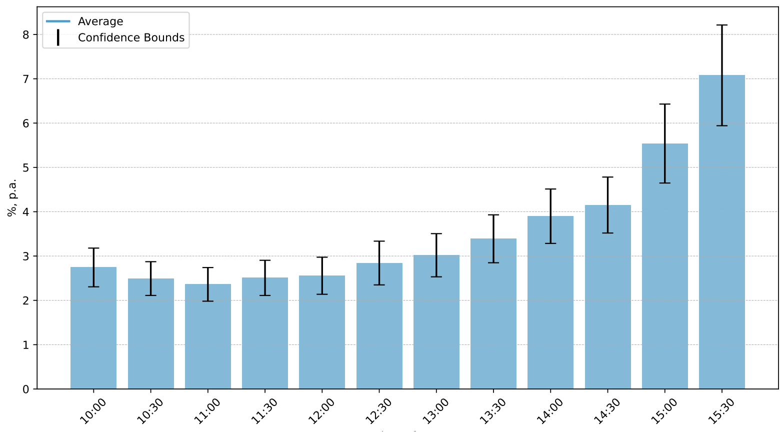

Figure IA.3: Variance Risk Premiums. The figure shows average variance risk premiums (VRP) for SPXW options by intraday 30-minute points for 0DTEs. VRP is computed as implied minus realized variances to expiration at 16:00 annualized using exact minutes to expiration and $365 \times 24 \times 60$ minutes per day. We use only 0DTE options and average realized VRPs from the end of each bar to expiration at 16:00 that day (with 95% confidence bounds based on Newey and West (1987) standard errors with one lag). The sample period is from 01/2012 to 14/06/2023.

To further understand whether the variance risk premium is linked to (or justified by) the risk of investment in options just hours (or minutes) before expiration, we analyze the dynamics of option investment performance at various points during the expiration day. At the end of each 30-minute bar, we select two calls, two puts, and two straddles with strike prices just around the current SPX level to be approximately ATM. Straddles are then close to being delta-neutral and call and put options close to 0.5 and -0.5 deltas, respectively. We compute the payoffs of these option positions using the SPX level at market close at 16:00 and then the realized return using the mid-prices at the end of the respective bar and the computed payoffs. We scale the returns to annual terms using the exact number of minutes to expiration and $60 \times 24 \times 365$ minutes per year. These realized returns are used to compute performance statistics (means, quartiles, and standard deviations of the distribution) for calls, puts, straddles, and all strategies combined in Figure IA.4 and for straddles in more detail in Table IA.9.

We observe that all the strategies reap negative returns on average, with the distribution being extremely wide and right-skewed, especially later in the day. Most importantly, the volatility of realized returns increases faster closer to expiration and jumps by a factor of 2 in the last bar. Average returns of the delta-neutral straddles, i.e., strategies closest to the pure volatility trade, are all negative and rapidly increasing in absolute value to the end of the day. In fact, the average return is an order of magnitude larger in the last to-expiration bar compared to the noon.

Table IA.9 shows that the risks for the delta-neutral straddles increase more or less proportionally to the expected returns. For all time points in the afternoon, the Sharpe ratios of investing into straddles are in the same ballpark. Because realized return distributions are very noisy and right-skewed, the Sharpe ratio may not be the best measure of risk-return trade-off. Nevertheless, combined with the pronounced return skewness, it follows that the increase in realized VRPs during the day we observed earlier closely tracks the dynamics of realized risks in terms of variance of returns. Therefore, 0DTEs do not stand out relative to other maturity buckets in terms of their risk-return trade-off, though they certainly have very distinct risk characteristics and, respectively, return profiles.

Variance Risk Premium and Open Interest Gamma To ascertain whether market participants price any perceived risks created by high dollar gamma values on options in different maturity buckets, we check how the variance risk premiums realized over a trading day and earned by selling 0DTEs and other options react to aggregate gamma levels. We estimate the

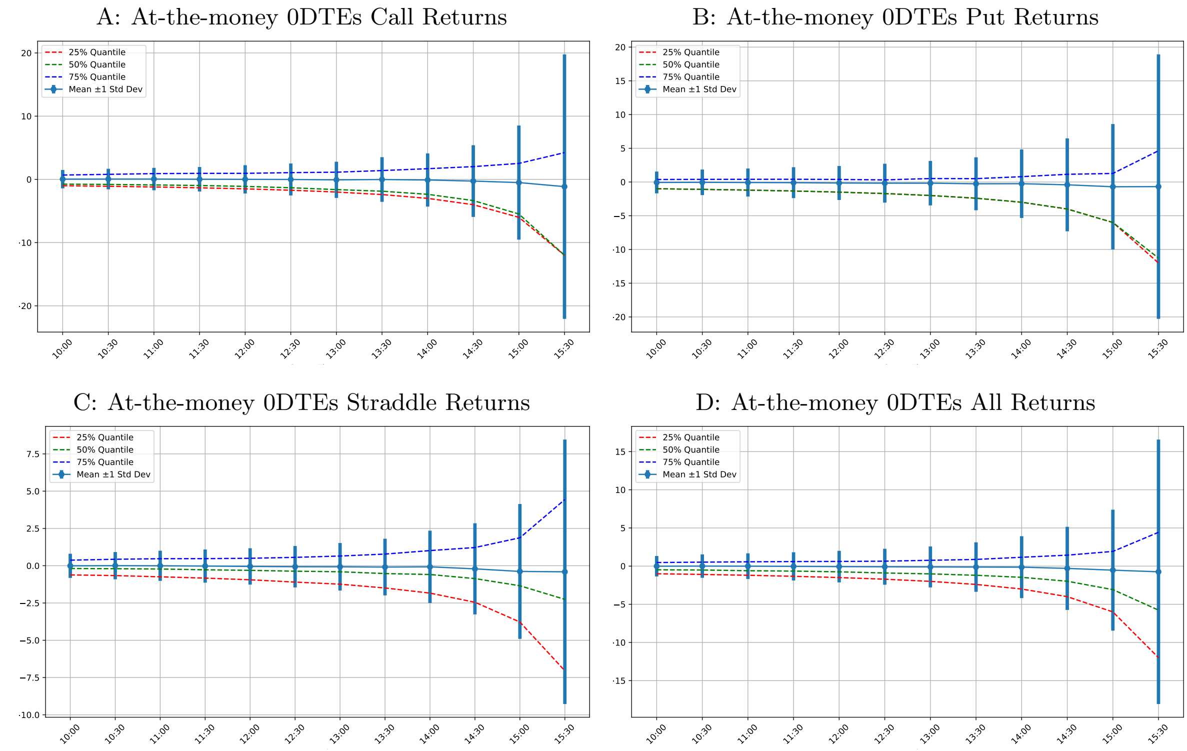

Figure IA.4: 0DTE Option Returns. The figure shows average returns to expiration for 0DTE SPXW options by intraday 30-minute points. At the end of each bar, we select two calls, two puts and two straddles with the strikes closest to the current SPX level, from both sides. We compute their holding returns to expiration at 16:00, and then compute statistics based on the distribution of these returns for a given time bar across all available days. Panels A, B, C, and D show statistics for calls, puts, straddles, and all combined, respectively. Returns are shown as decimals scaled to a 6-hour period (i.e., scaled by 6/(hours to expiration)). The sample period is from 01/2012 to 14/06/2023.

Bar End Time	Count	Mean	Volatility	Min	25%	50%	75%	Max	Skew	SR, p.a.
10:00:00	2734	-0.0069	0.810	-0.998	-0.617	-0.186	0.373	5.366	1.484	-0.134
10:30:00	2734	0.0031	0.913	-1.089	-0.661	-0.201	0.432	8.918	2.034	0.054
11:00:00	2734	-0.0062	1.011	-1.200	-0.745	-0.221	0.470	9.462	2.045	-0.097
11:30:00	2734	-0.0249	1.111	-1.333	-0.831	-0.274	0.475	10.550	2.128	-0.355
12:00:00	2734	-0.0484	1.219	-1.500	-0.944	-0.311	0.498	11.076	2.023	-0.630
12:30:00	2734	-0.0668	1.389	-1.712	-1.098	-0.368	0.560	9.436	1.806	-0.764
13:00:00	2732	-0.0714	1.593	-2.000	-1.239	-0.405	0.650	12.173	1.693	-0.711
13:30:00	2696	-0.0912	1.900	-2.400	-1.493	-0.526	0.780	15.086	1.695	-0.762
14:00:00	2696	-0.0748	2.424	-2.994	-1.837	-0.590	1.015	19.547	1.890	-0.490
14:30:00	2696	-0.2098	3.056	-4.000	-2.451	-0.864	1.219	22.328	1.620	-1.090
15:00:00	2696	-0.3843	4.523	-5.996	-3.777	-1.344	1.874	36.143	1.621	-1.349
15:30:00	2696	-0.4081	8.869	-11.968	-7.047	-2.257	4.440	73.185	1.504	-0.731

Table IA.9: At-the-money 0DTEs Straddles Returns to Expiration. The table shows average returns for 0DTE SPXW options by intraday 30-minute points. At the end of each bar, we select two straddles with the strike being closest to and from both sides from the current SPX level; we compute their holding returns to expiration at 16:00 and then compute statistics based on the distribution of these returns for a given time bar across all available days. Returns are scaled to the 6-hour equivalent (i.e., scaled by 6/(hours to expiration)), and Sharpe ratio (SR) computed from these returns is additionally scaled up by $\sqrt{252}$ to be in approximately annual terms. The sample period is from 01/2012 to 14/06/2023.

following regression

$$VRP^{\Delta}_{dte,d} = b_0 + OI^{\$\Gamma}_{dte,d} \times (b_1 + b_2 \ln RV^{on}_d + b_3 VRP^{\Delta}_{dte,d-1}) + \mathbf{CX} + \varepsilon_d, \tag{IA.1.7}$$

where $VRP^{\Delta}_{dte,d}$ is the realized VRP from 10:00 to 16:00 on day d computed from implied variance on SPXW options and realized variance of SPX index, aggregated by DTE buckets, $OI^{\$\Gamma}_{dte,d}$ is the open interest dollar gamma at 10:00 on day d, aggregated by DTE buckets for all SPXW and SPY options, and $\mathbf{X}$ is a vector of controls including two lags of the dependent variable, log of the current overnight variance RV^{on}_d of SPX index, and year dummies. Note that we do not directly control lagged intraday variance because it is part of the lagged VRP^{Δ}. We standardize the dollar gamma levels for each DTE bucket to unit variance to make coefficients comparable.

The results reported in Table IA.10 corroborate our findings in the main analysis, showing that realized risk premiums decline following an increase in the preceding day's VRP and open interest gamma at market open, respectively. The interaction terms with lagged intraday variance in Table 5 and with lagged variance risk premium in Table IA.10 are both negative, even though the VRP^{Δ} expression includes RV^{day} with a *negative* sign. These results indicate that the decline in the realized variance risk premiums today is driven predominantly by lower option prices, which overcompensate for a lower realization of intraday variance.

IA.1.5 Real Uses of 0DTEs: Short-term Bets

Our results so far indicate that 0DTEs do not stand out from other longer maturity options on the basis of their market-destabilizing effect. Instead, 0DTEs stand out mainly based on their extremely high ex-post variance risk premium, especially in the last hours before expiration, which we link to the convexly increasing leverage, gamma risk, and the speed of time decay of 0DTEs shortly before expiration. Maximum payoffs from the ATM straddles in Table IA.9 are truly stunning, and even though mean (and median) returns are increasingly negative and volatile, many retail investors may be attracted by the lottery characteristics of the payoffs.

Because these different characteristics of 0DTEs make them suitable for event-based trading, we analyze 0DTEs' trading activity and realized variance risk premiums around Federal Open

	$VRP^{\$\Delta}_{dte,d}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV^{on}_d$	0.020	-0.003	0.025	0.035	0.073
	(0.018)	(0.013)	(0.032)	(0.050)	(0.083)
$OI^{\$\Gamma}_{dte,d} \times VRP_{d-1}$	-5.666***	-3.996***	-2.311**	0.731	-0.253
	(1.439)	(0.951)	(1.171)	(1.022)	(0.906)
$OI^{\$\Gamma}_{dte,d}$	0.301	-0.046	0.341	0.236	0.606
	(0.237)	(0.178)	(0.444)	(0.672)	(1.148)
$\ln RV^{on}_d$	-0.004	0.002	-0.010	-0.014	-0.027
	(0.004)	(0.002)	(0.007)	(0.010)	(0.019)
VRP_{d-1}	0.851***	0.572***	0.453**	-0.045	0.099
	(0.176)	(0.116)	(0.214)	(0.146)	(0.161)
VRP_{d-2}	0.199***	0.250***	0.120	0.042	-0.045
	(0.065)	(0.046)	(0.085)	(0.063)	(0.045)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.636	0.492	0.105	0.010	0.009
Obs.	1,377	1,372	2,444	2,523	2,733

Table IA.10: Variance Risk Premium and Open Interest Gamma. This table reports the results of a regression of the annualized variance risk premium realized on day d on the level of overnight variance and lagged variance risk premium both interacted with open interest dollar gamma by DTE buckets, using the specification in (IA.1.7). Open interest is recorded at market open and converted to dollar gamma $OI^{\$\Gamma}_{dte,d}$ using underlying prices, and each option gamma levels at 10:00 ET on day d. The variance risk premium (VRP^{Δ}) realized on a given day d is computed as the ex-post VRP to expiration for the SPXW options for a given DTE at 10:00 on day d minus the ex-post VRP to expiration at 16:00 of the same day. Then, the realized VRP^{Δ}'s are scaled to annual terms and averaged on each day d across DTEs in a given DTE bucket. The realized variance in the VRP calculation and the overnight variance are computed from the intraday and overnight returns for the SPX index, respectively. Dollar gammas are aggregated from the SPXW and SPY options with moneyness levels in $[0.5, 1.5]$ for each DTE bucket. Dollar gamma levels are standardized to unit variance and then divided by 10. Newey and West (1987) standard errors with five lags are in parentheses. The sample period is from 01/2012 to 14/06/2023.

Market Committee (FOMC) decision announcements, which are associated with the resolution of uncertainty (e.g., Cieslak, Morse, and Vissing-Jorgensen 2019, Ai, Han, Pan, and Xu 2022). The analysis allows us to establish whether 0DTEs are actually used in the market settings where they should be especially useful. We look at two 30-minute bars before the FOMC announcement and the remaining time to market close after the FOMC announcement. We have 92 FOMC announcements between 2012 and mid-June 2023. The majority (84) occurred at 14:00, three at 12:30, and three at 14:15.[23]

[23]For this section, we use options data based on 30-minute bars. If an announcement is in the middle of a 30-minute bar end, we assign it to the bar end.

First, we regress delta dollar trading volume (in billions) at a 30-minute frequency on indicator variables for periods around FOMC announcements as follows:

$$Vol^{\$\Delta}_{dte,d:t} = b_0 + b_1 \mathbb{1}(\textit{Before FOMC})_{d:t} + b_2 \mathbb{1}(\textit{After FOMC})_{d:t} + \mathbf{CX} + \varepsilon_{d:t}. \tag{IA.1.8}$$

$Vol^{\$\Delta}_{dte,d:t}$ is the total (absolute) delta dollar volume for all options within a given DTE bucket and moneyness in $[0.5, 1.5]$ range, as defined in equation (5), $\mathbb{1}(\textit{Before FOMC})_{d:t}$ is an indicator variable that equals one if $d : t$ falls within the one-hour window before an FOMC announcement. $\mathbb{1}(\textit{After FOMC})_{d:t}$ is an indicator variable that equals one if $d : t$ falls within the remaining trading hours after an FOMC announcement on day d. Coefficients b_1 and b_2 capture the average change in options trading activity (in billions of dollars per 30-minute bar) before and after FOMC announcements, respectively, relative to other intraday periods not adjacent to FOMC announcements and accounting for various time-fixed effects captured by $\mathbf{X}$, namely year, month, day of the week, and time of day effects. We group the time of the day into three buckets, morning, afternoon and evening, and then use these buckets in the controls.

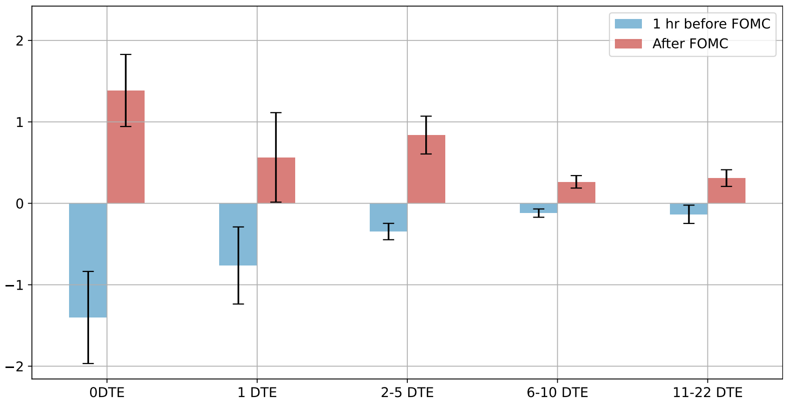

Figure IA.5: Option Trading Volume Around FOMC Announcement by DTE. This Figure reports the coefficient estimates and the 95% confidence bounds from regressing dollar delta volume (in billions) at a 30-minute frequency on indicator variables for periods around FOMC announcements, as specified in equation (IA.1.8). We estimate the regression separately for the different DTE buckets on the x-axis. Confidence bounds are based on Newey and West (1987) standard errors with five lags. The sample period is from 01/2012 to 14/06/2023.

Figure IA.5 shows that options in all DTE buckets experience a significant reduction in trading volume before the FOMC decision and an almost symmetric increase in activity after the announcement. Most of the volume is traded in the options within five working days to expiration, with 0DTEs volume decrease and subsequent increase before and after FOMC being almost twice larger compared to other buckets.

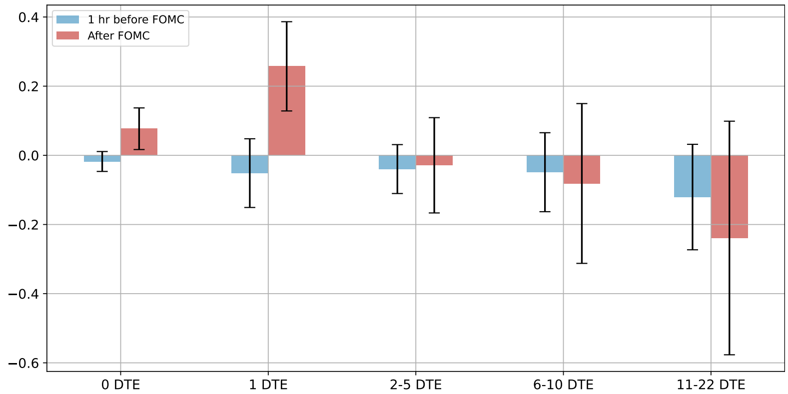

Figure IA.6: Realized VRP Around FOMC Announcement by DTE. This Figure reports coefficient estimates and the 95% confidence intervals from regressing the realized variance risk premium (VRP^{Δ} in % p.a.) for each intraday 30-minute bar on indicator variables for periods around FOMC announcements based on a version of equation (IA.1.8) that uses VRP^{Δ} as the dependent variable. We estimate the regression separately for the different DTE buckets on the x-axis. Confidence bounds are based on Newey and West (1987) standard errors with five lags. The sample period is from 01/2012 to 14/06/2023.

Second, we run a similar regression for the realized variance risk premiums by using the realized variance risk premium for each 30-minute bar $d:t$ defined in equation (IA.1.6) for a DTE bucket dte (i.e., $VRP^{\$\Delta}_{dte,d:t,30m}$) on the left-hand side of equation (IA.1.8). Figure IA.6 shows that the realized VRPs before the FOMC are all close to zero and insignificant. It indicates stable prices before an announcement, i.e., changes in implied variances over the period are almost perfectly matched with the realized variance. After the announcement, however, we observe high and significant payoffs from selling short-term variance, especially pronounced for 1DTE options, for which time decay has not yet eliminated most of the time value.

Thus, trading in short-term options around FOMC announcements is akin to betting on the resolution of short-term uncertainty: one builds up and keeps short volatility positions in times of elevated uncertainty, and hence, high *ex-ante* variance risk premium (e.g., Bali and Zhou 2016), and liquidates them after the uncertainty is resolved and prices settle down. The other side, the option buyers, are betting on (or hedging) a directional market move after the FOMC decision at a high relative price but still cheaper in absolute terms compared to using longer-term options. Longer-term options, with maturities exceeding one day, retain much of their value beyond the period influenced by FOMC-related uncertainty, and their premiums are not significantly eroded by time decay yet. As a result, they are not well suited for making short-term directional and volatility bets.

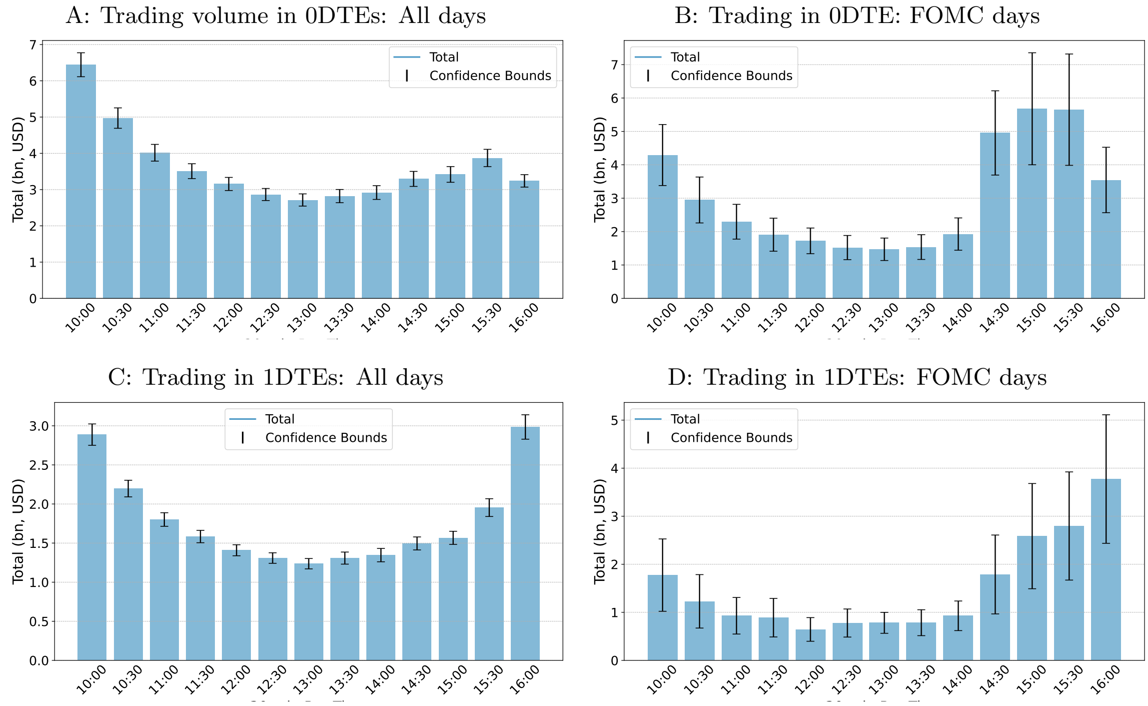

Figure IA.7: Trading Volume by DTEs and Intraday Bars: FOMC Effect. This Figure reports average trading volume (in terms of dollar delta) for SPXW and SPY options, separately for 0- and 1DTEs, and the 95% confidence intervals for each intraday 30-minute bar for all days in the sample and for days with FOMC announcements, respectively. Confidence bounds are based on Newey and West (1987) standard errors with one lag).The sample period is from 01/2012 to 14/06/2023.

Simply looking at the average trading volumes and realized VRPs by intraday bars without including any fixed effects and not accounting for the exact announcement time, we observe distinct patterns of trading volume (Figure IA.7) and realized VRPs (Figure IA.8) on FOMC days. There is a clear reduction in trading before the FOMC decision announcement and a spike afterward.[24] The realized variance risk premiums are quite different on FOMC days, with short volatility positions in 0DTE losing or not making money throughout the day of FOMC before the announcement and then making (all the) profits within the bar after the announcement. Unconditionally, 0DTE realized variance risk premium is positive for all 30-minute bars and is significant for half of them. For 1DTEs, unconditionally, all the variance risk premium one

[24]The other DTE buckets demonstrate similar changes in trading patterns consistent with Figure IA.5.

day before expiration is realized in the last 30 minutes before 16:00, while for FOMC days this period shifts to the right after announcement.[25]

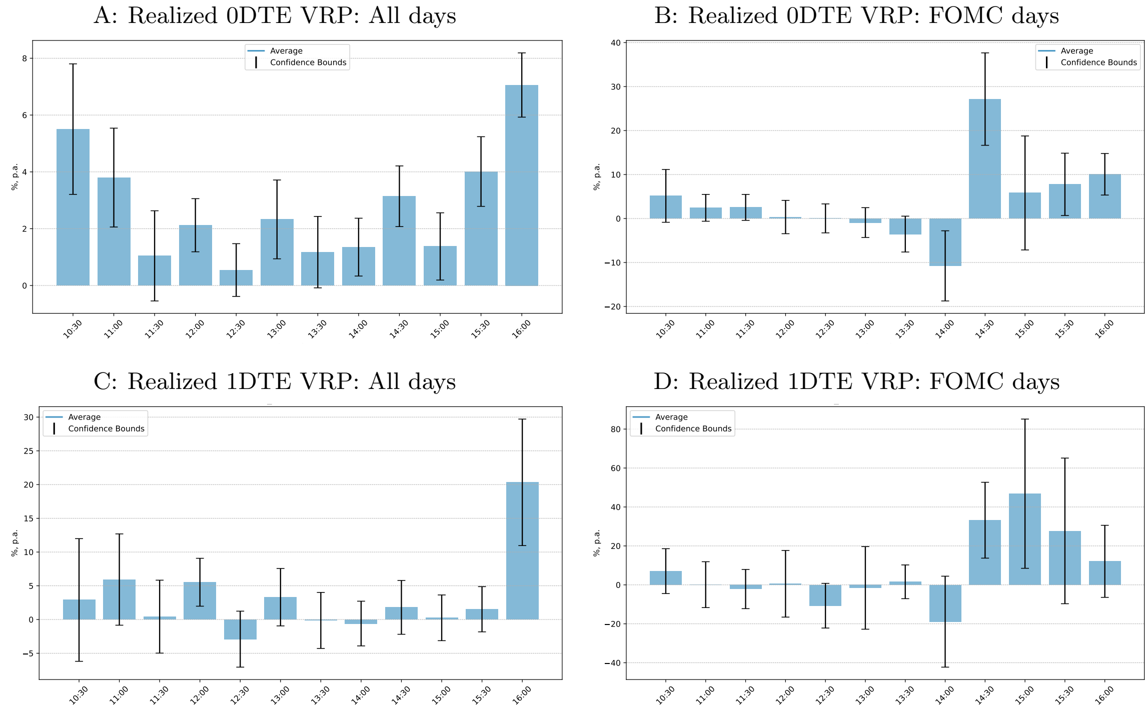

Figure IA.8: Realized VRP by DTEs and Intraday Bars: FOMC Effect. This Figure reports average realized ex post VRP^{Δ} (in % p.a.) for SPXW options, separately for 0- and 1DTEs, and the 95% confidence intervals for each intraday 30-minute bar for all days in the sample and for days with FOMC announcements, respectively. Confidence bounds are based on Newey and West (1987) standard errors with one lag). The sample period is from 01/2012 to 14/06/2023.

[25] In unreported results, we do not observe any significant changes in realized VRP for longer-term options.