0DTEs: Trading, Gamma Risk and Volatility Propagation*

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Abstract

Investors fear that surging volumes in short-term, especially same-day expiry (0DTE), options can destabilize markets by propagating large price jumps. Contrary to the intuition that 0DTE sellers predominantly generate delta-hedging flows that aggravate market moves, high open interest gamma in 0DTEs does *not* propagate past volatility. 0DTEs and underlying markets have become more integrated over time, leading to a marginally stronger link between the index volatility and 0DTE trading. Nonetheless, intraday 0DTE trading volume shocks do not amplify recent past index returns, inconsistent with the view that 0DTEs market growth intensifies market fragility.

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

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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, 0DTE options 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 needs that can destabilize the underlying market, even when the underlying market is very liquid, as is the case for the SPX index-based exchange-traded fund (ETF) SPY and S&P500 E-Mini (ES) Futures.[3]

The rationale behind these concerns is that when 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. Cboe disputes such scenarios, claiming that the trading flows and the resulting market makers' exposure during the day are well-balanced. Hu, Kirilova, and Muravyev (2023) show that option market makers primarily use active inventory rebalancing instead of delta-hedging to manage risk, indicating that the underlying asset return shocks may not be intensified by 0DTE options' positions.

[1] Cboe Insights at 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.

This paper investigates these opposing arguments and documents several novel features of the 0DTE market for the SPY and SPX weekly options. In line with the extant literature (e.g., Almeida, Freire, and Hizmeri 2023, Bandi, Fusari, and Renò 2023), we show that volume in 0DTEs now dominates options trading in these underlying markets and that 0DTEs pay exceptionally high variance risk premium (before transaction costs) in annual terms. To understand whether the growth of short-term options markets can harm underlying market stability by creating extreme volatility events or propagating past volatility, we separately analyze the effects of the intraday trading activity and of the potential rebalancing needs after large underlying market moves, as inferred from the open interest gamma.

First, to understand whether 0DTE option trading is increasingly linked to trading in the underlying market instruments or boosts market short-term volatility, we use a structural vector autoregression framework to analyze joint intraday dynamics of the magnitude of realized returns and trading volume in the 0DTE options and the underlying instruments. 0DTEs and underlying markets are rapidly becoming more integrated, with the correlation of their intraday trading volume increasing from 0.25-0.30 before 2021 to 0.59 in 2023. Positive shocks to 0DTE trading volume in recent years are indeed 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 return react stronger to shocks to 0DTE trading volume relative to earlier periods when 0DTE trading was negligible. However, the difference in the magnitude of the average volatility response to 0DTE trading across the early and later sample period amounts to only 0.15 standard deviations of the return volatility, 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. We also 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. While we observe a clear time trend in the average intensity of shock propagation from 0DTE trading to the underlying market, we do not find supportive evidence that sharp intraday jumps in 0DTE trading propagate past market moves and lead to extreme intraday returns.

Second, we analyze how the aggregate dollar gamma of open option positions of different maturities shapes the subsequent intraday underlying index realized volatility, unconditionally and conditional on past volatility. The average daily open interest gamma did not grow after 2016, neither for 0DTEs nor for the other maturities, suggesting that even if short gamma investors systematically delta-hedge, the 0DTEs market growth is unlikely to have exacerbated the effects of such hedging activity. Indeed, we do not find evidence that the 0DTEs' open interest gamma propagates or unconditionally increases the underlying index volatility. Moreover, for options with more than one day to expiry, open interest gamma is associated with lower realized volatility within the day.

Three important considerations are worth noting in light of the above result. First, one cannot generally identify the effect of open interest gamma on volatility without knowing the aggregate gamma dynamics of delta-hedgers (Ni, Pearson, Poteshman, and White 2021). However, in recent years, investors have been increasingly selling volatility for yield enhancing (e.g., BIS 2024), resulting in long gamma positions of delta-hedgers. In this case, delta-hedging would dampen price swings since traders with long gamma positions would sell after the underlying price goes up and buy after the price goes down. Second, anecdotal evidence suggests that due to 0DTEs' very high gamma, traders often rebalance 0DTE positions directly instead of trading delta in the underlying markets.[4] Moreover, while the gammas of at-the-money (ATM) options increase rapidly closer to expiry (for an ATM call with an implied volatility of 20%, the one-hour option's gamma is roughly 25 times that of the one-month's), the gammas of even

[4]See the discussion in Section 4.1.

slightly not-ATM options decay very quickly on the expiry day. As a result, rebalancing needs for a 0DTE portfolio are concentrated in ATM options and can dissipate quickly as the option portfolio moves away from ATM.[5] Overall, these considerations point to justifications for why activity in the 0DTEs market may not amplify and could even dampen the volatility of the underlying. To the best of our knowledge, our paper is the first to systematically study the effects of aggregate gamma exposure in 0DTEs. Our findings contrast those of Anderegg, Ulmann, and Sornette (2022), Soebhag (2023) and Brogaard, Han, and Won (2023), which either analyze different markets or focus on option volume instead of gamma exposure.

We assess features of 0DTE options that differentiate them from the more familiar longer-term options and the implications for risks associated with 0DTE options trading. We document negative average returns, Sharpe ratios, extreme volatility, and positive skewness for 0DTE options trading — all intensifying as the expiration approaches. Similarly, 0DTE options exhibit exceptionally high variance risk premium (VRP)—measured as the realized return on a short variance swap, i.e., the difference between implied and realized variances up to a particular expiration date—which increases as expiration approaches. The average annualized VRP for 0DTEs is roughly five times that of the 11-22 DTE options and is orders of magnitude larger than that of the longer maturity buckets (1 to 22 DTEs) for every year in our sample. At the same time, in daily terms, the 0DTE's VRP is only about 0.01%, which makes it hardly profitable given the required delta-hedging intensity for high-gamma instruments and realistic transaction costs. Overall, the 0DTE options' VRP dynamics and those of the returns, volatility, skewness, and Sharpe ratios from the 0DTE options trading suggest a close alignment between realized risks and expected returns. As such, the burgeoning demand for 0DTEs options could be rationalized partly by investors' lottery-type preferences because of the high positive skewness.

[5]We thank Jefferson Duarte for bringing up this point.

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 zero- and one-day-to-expiry options, to bet on the resolution of uncertainty. 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.

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 total rebalancing risks of the aggregate open positions in 0DTEs vs. longer-maturity options and 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]

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

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

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 relate to the empirical literature on the impact of option trading and open interest on the underlying.[7] 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. 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) show that shocks to retail option trading due to Robinhood's introduction of options increased optionable stocks' return volatility. 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. We differ from these papers in that we analyze 0DTE options, a relatively new and evolving market development whose potential impacts are not yet fully understood.

[7] A related literature studies the impact of inverted demand in ETF rebalancing (e.g., Shum, Hejazi, Haryanto, and Rodier 2015, Augustin, Cheng, and den Bergen 2021, Baltussen, Da, Lammers, and Martens 2021).

We also add to a well-developed literature analyzing 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) derive an equilibrium model for studying the term structure of variance risk premia. Coval and Shumway (2001) show that zero-beta straddles produce negative returns. Londono and Samadi (2024) 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. Constantinides, Jackwerth, and Savov (2013) document a decreasing term structure of volatility and skewness for leverage-unadjusted option returns, with positive skewness for maturities between 30 and 90 days. We observe a similar but more extreme picture for shorter maturity options. Moreover, we document negative returns to expiry for both calls and puts, while the authors document, on average, positive point estimates for out-the-money call returns.

Overall, we complement the above 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 the expiry time, which is linked to an increasing realized volatility and skewness of delta-neutral strategy returns. To our knowledge, our paper is the first to document (i) the negative association between 0DTE open interest gamma and the intraday realized variance risk premium conditional on the lagged realized VRP and (ii) analyze the joint dynamics of intraday 0DTE index option trading and underlying volatility.

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. In Section 5, we consider potential uses of 0DTEs as short-term bets on the resolution of uncertainty. Section 6 presents robustness tests and additional analysis, and Section 7 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 data for several underlying instruments representing the broad U.S. stock market, with the following option roots: SPXW, European type and cash-settled against the close (16:00 ET) of the S&P500 market index and SPY written on the most actively traded S&P500 exchange-traded fund (ETF), American type and settled physically in the evening of the expiration date. Note that 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. At the time of analysis (August 2023), Cboe offers options on the S&P500 index and SPY with expiration on each day for the next month. 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.

We use two source data formats for the options: intraday bars and actual transactions. Intraday bars from Cboe DataShop are recorded at 30 minute frequency, and they 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). Most computations are based on these intraday bars, and because the data is cleaned by Cboe, there is not much pre-processing or filtering required. Transactions data from Cboe DataShop represents enhanced data from the Options Price Reporting Authority (OPRA), and 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 is not cleaned by the provider, and we parse it using filters and procedures similar to Bryzgalova, Pavlova, and Sikorskaya (2023).[8] 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, standing for SPX Weeklys options and options on the most actively traded exchange-traded fund SPY, respectively), 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 has one DTE). We compute various market statistics for the options up to 22-DTEs and then concentrate in more detail on options with extremely short maturities (0- and 1-DTEs).

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*.[9]

[8] 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 the original paper), and `trade_price` between `best_bid - spread` and `best_ask + spread`.

[9] 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 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.

2.2 Construction of Main Variables

Returns, Variances and Variance Risk Premiums. 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:

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

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 compute realized variance (RV) from 1-minute prices at the end of each 30-minute bar for periods matching each computed IV by adapting the methodology of Hansen and Lunde (2005). For the expiration on the same day (i.e., for 0DTEs) realized variance is just the sum of squared one-minute log returns from the end of a bar to the end of the day:

$$RV_{j,dte=0,d:t} = \sum_t^{T-1} r_{t,t+1}^2, \tag{2}$$

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. We compute overnight returns from close at 16:00 on the previous day to open at 9:31 in the morning.[10] For longer periods, the realized variance is the sum of variance from a given bar until the end of the day $RV_{j,dte=0,d:t}$, and a weighted sum of overnight and intraday variances for the following full days until expiration:

$$RV_{j,dte,d:t} = RV_{j,dte=0,d:t} + \omega_1 RV^{on}_{j,dte,d} + \omega_2 RV^{day}_{j,dte,d}, \tag{3}$$

where $RV^{on}_{j,dte,d}$ is the sum of squared overnight log returns from the close of day d until expiration corresponding to dte, and $RV^{day}_{j,dte,d}$ is the sum of intraday log returns from day $d+1$ until expiration corresponding to dte. 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 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:

$$VRP_{j,dte,d:t} = IV_{j,dte,d:t} - RV_{j,dte,d:t}. \tag{4}$$

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 $d:t$:

$$VRP^{\Delta}_{j,dte,d:t,\Delta t} = VRP_{j,dte,d:t-\Delta t} - VRP_{j,dte,d:t}, \tag{5}$$

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

[10] We include the first two minutes 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.

Trading Activity and Risk Variables. To quantify market activity and dynamics of risks stemming from the open option positions, we define and compute several variables, specified in dollars and not in the number of contracts, for comparison across instruments and time. All variables are computed conditional on several dimensions (underlying instrument j, option type $cp \in \{C(all), P(ut)\}$, trading days to expiration dte, and time $d:t$ consisting of date d and end-of-bar time t (we omit the length of a bar for brevity, and note the frequency in text), and moneyness bucket $\mathcal{K}$). Each of these dimensions can be integrated out subsequently. We add up a specific characteristic of interest within each moneyness bucket to arrive at the total exposure from all options within a particular range of strikes.

We define three open interest-based measures: dollar-notional open interest ($OI^{\$}_{j,cp,dte,d:t,\mathcal{K}}$), delta-dollars open interest ($OI^{\$\Delta}_{j,cp,dte,d:t,\mathcal{K}}$), and gamma-dollars open interest ($OI^{\$\Gamma}_{j,cp,dte,d:t,\mathcal{K}}$). While the first variable quantifies the overall exposure in terms of dollar notional, delta-dollars open interest quantifies the change in position value for small changes in underlying, and the gamma-dollars open interest gives the rebalancing needs of all open positions to maintain delta neutrality after a small change in underlying price.

$$OI^{\$}_{j,cp,dte,d:t,\mathcal{K}} = \sum_{K \in \mathcal{K}} OI(O_{j,cp,dte,d:t,K}) \times 100 \times S_{j,d:t}, \tag{6}$$

$$OI^{\$\Delta}_{j,cp,dte,d:t,\mathcal{K}} = \sum_{K \in \mathcal{K}} OI(O_{j,cp,dte,d:t,K}) \times 100 \times \Delta(O_{j,cp,dte,d:t,K}) \times S_{j,d:t}, \tag{7}$$

$$OI^{\$\Gamma}_{j,cp,dte,d:t,\mathcal{K}} = \sum_{K \in \mathcal{K}} OI(O_{j,cp,dte,d:t,K}) \times 100 \times \Gamma(O_{j,cp,dte,d:t,K}) \times S^2_{j,d:t}, \tag{8}$$

where $OI(O)$ is the open interest in contracts at the beginning of day d for the option contract O, the $S_{j,d:t}$ is the price of underlying at the end of bar $d:t$, $\Delta(O)$ and $\Gamma(O)$ are delta and gamma of the option O.

We define the delta-dollar trading volume $Vol^{\$\Delta}_{j,cp,dte,d:t,\mathcal{K}}$ that measures the dollar turnover in terms of the risk traded (i.e., dollar notional times absolute delta of an option):

$$Vol^{\$\Delta}_{j,cp,dte,d:t,\mathcal{K}} = \sum_{K\in\mathcal{K}} Vol(O_{j,cp,dte,d:t,K}) \times 100 \times |\Delta(O_{j,cp,dte,d:t,K})| \times S_{j,d:t}, \tag{9}$$

where $Vol(O)$ is the number of contracts of option O traded during bar $d:t$. We compute dollar volume $Vol^{\$}_{j,d:t}$ for underlying instruments j similarly by adding up dollar values of all trades within a given bar ending at $d:t$.

3 0DTE vs. Longer-term Options

This section analyzes in Section 3.1 the dynamics of trading volumes and aggregate risks for options of various maturities, and then in Section 3.2 documents the returns, risks and variance risk premiums priced in ultra-short-term options.[11]

3.1 Trading Volumes and Aggregate Risks

We look at the overall market statistics for options maturing in the next 22 trading days (i.e., one calendar month), specifically 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 shorter-term options from the longer-term ones.

For analyzing market composition and its dynamics, we aggregate 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 expressions for open interest in equations (6) to (8) and dollar volume in equation (9). 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 options with moneyness $K \in [0.5, 1.5]$. For volume, we add up all observations of all options in the selected moneyness range during the day. To compute the open

[11]For this section, we use options data based on 30-minute bars.

interest and volume variables for DTE buckets, on each day d we sum up aggregate variables over the required dte range.

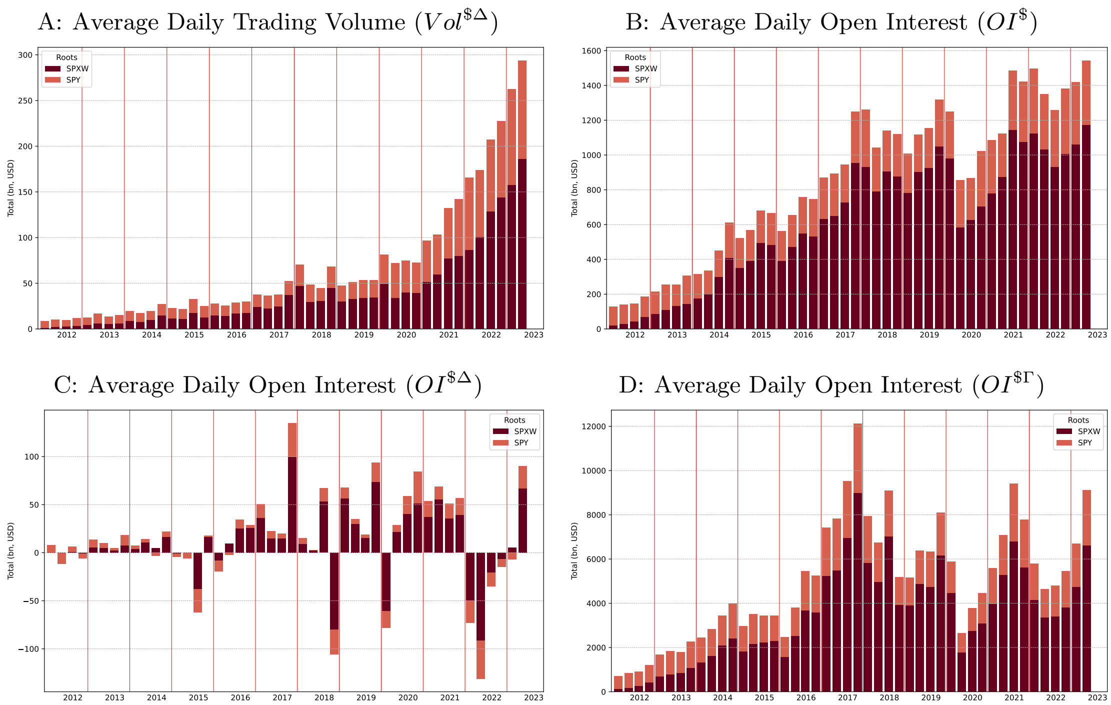

Figure 1: Aggregate Market Statistics. The figure shows quarterly averages of daily volume and open interest variables for SPXW and SPY options expiring within the next 22 trading days. We aggregate variables in equations (6) to (9) on each day by integrating out option type, days to expiration and time of day for moneyness range $[0.5, 1.5]$, and compute quarterly averages. The sample period is from 01/2012 to 14/06/2023.

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. We know that SPY options are popular among individual investors due to the low notional value of the contract (1/10 of the index option's notional). Accordingly, the average trading volume in Panel A for SPY is relatively high—about 50% 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.

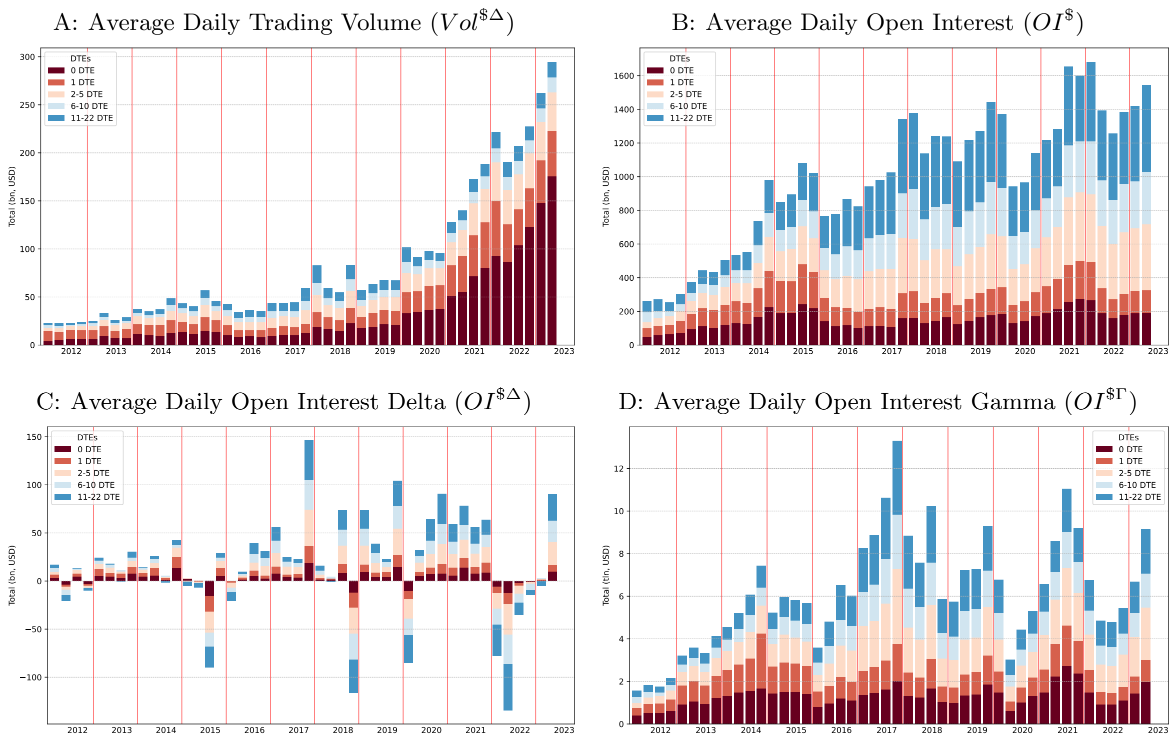

Figure 2: Market Statistics by Days to Expiration. The figure shows quarterly averages of daily volume and open interest variables for SPXW and SPY options by DTE buckets (0, 1, 2-5, 6-10, 11-22 trading days to expiration). We aggregate variables in equations (6) to (9) on each day by integrating out option type and time of day for moneyness range $[0.5, 1.5]$ and pre-defined DTE ranges, 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 largely due to the 0DTEs, for which the depicted evolution of trading volume resembles a quadratic function. Second, 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 in terms of dollar gamma are relatively stable over the years and are comparable across DTE buckets. The pattern fits well with the intuition that the direction of risk taken daily in extremely short-term options changes often 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, the introduction of 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, we are reluctant to link it to COVID-related trading.

	Count	Mean	StDev	Min	25%	50%	75%	Max
Full Sample Period								
Trade Volume (USD, bn)	1433	192.6	204.9	4.1	40.3	89.7	303.8	854.4
Trade Volume Delta (USD, bn)	1433	47.0	49.6	1.3	11.8	23.4	71.2	227.1
Open Interest (USD, bn)	1433	163.2	111.8	11.3	78.8	133.1	216.5	720.7
Open Interest Delta (USD, bn)	1433	3.1	18.9	-135.4	-3.8	2.9	11.3	106.6
Open Interest Gamma (USD, bn)	1433	1376.0	900.9	7.0	714.4	1173.6	1776.1	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)	866	133.7	113.5	8.8	50.0	91.0	193.7	537.1
Trade Volume Delta (USD, bn)	866	33.0	26.9	2.0	13.8	23.3	45.4	132.5
Open Interest (USD, bn)	866	167.8	115.9	18.6	75.4	130.8	236.4	600.3
Open Interest Delta (USD, bn)	866	4.5	19.7	-135.4	-2.8	3.8	12.5	106.6
Open Interest Gamma (USD, bn)	866	1503.0	986.8	131.3	766.6	1231.0	2018.5	7245.7
After 04/2022								
Trade Volume (USD, bn)	280	541.8	121.8	227.6	466.2	539.8	626.6	854.4
Trade Volume Delta (USD, bn)	280	128.8	39.9	39.7	101.0	128.8	155.5	227.1
Open Interest (USD, bn)	280	178.2	123.1	41.1	103.6	142.1	182.7	720.7
Open Interest Delta (USD, bn)	280	-0.5	20.3	-106.8	-6.8	0.6	8.2	72.7
Open Interest Gamma (USD, bn)	280	1248.5	781.0	157.5	697.7	1108.3	1613.1	5944.2

Table 1: 0DTEs Volume and Open Interest. The table provides statistics for the selected open interest and volume variables defined in equations (6) to (9) for all options with roots SPY and SPXW and zero days to expiration (0DTEs). The variables are first aggregated for each day: open interest variables use open interest in terms of number of contracts at the beginning of a 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. 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 summary. The sample period is from 01/2012 to 14/06/2023.

Table 1 provides more detailed summary statistics of 0DTEs volume and 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 sufficient daily liquidity. The variability of the open interest dollar delta is largely around a relatively moderate mean value, which indicates that 0DTEs are actively used in betting on direction. Aggregate rebalancing risks of open positions, as revealed by dollar gammas, are stable over time (1-1.4 tln on average) but demonstrate a pronounced right skewness with maximum values of 6-7 tln per day, which is more than six sigmas (StDev) from the mean. Such gamma concentrations can pose a real systemic risk for the market in case of sudden price jumps in the underlying. 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 Option Risks, Returns, and Variance Risk Premiums

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 (4) 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.[12] The average VRPs by DTE buckets and years shown in Figure 3, Panel A, clearly demonstrate the distinction between 0DTEs and *all other* maturities: zero-day-to-expiration options are far more expensive

[12] We use only SPXW root for VRP and option return computations because the integrated implied variance formulas as in (2.2) assume European options and cash settlement of index options make subsequent option return computations more transparent.

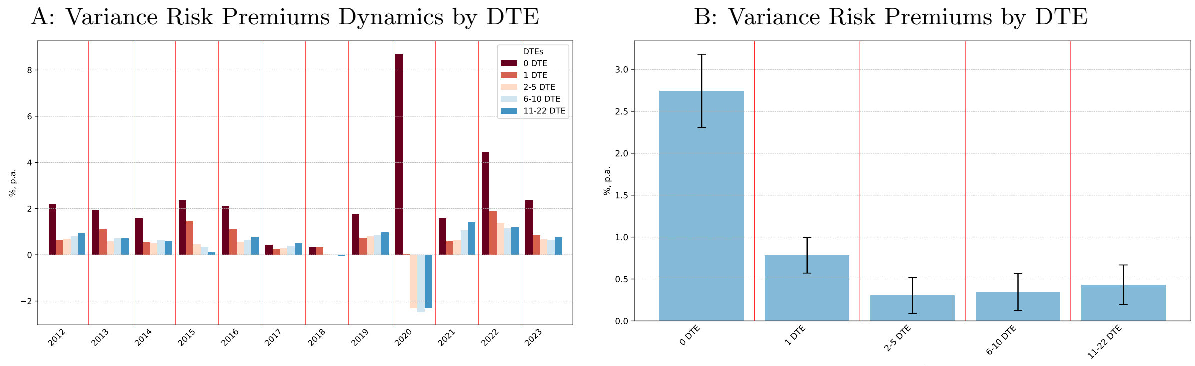

Figure 3: Variance Risk Premiums. The figure shows average variance risk premiums (VRP) for SPXW options by DTE buckets and years (Panel A) and by DTE buckets (Panel B). VRP is computed as implied minus realized variances to expiration at 16:00 annualized using exact minutes to expiration and $365 \times 24 \times 60$ 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.

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 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 4 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

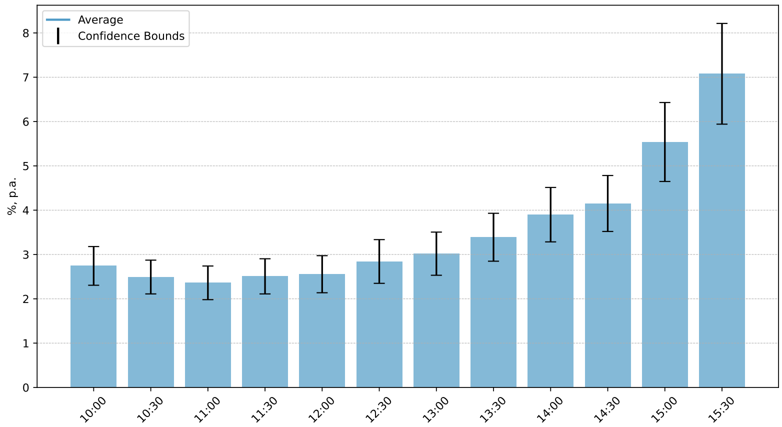

Figure 4: Variance Risk Premiums. The figure shows average variance risk premiums (VRP) for SPXW options by intraday 30-minute points for 0DTEs. VRP is computed as implied minus realized variances to expiration at 16:00 annualized using exact minutes to expiration and $365 \times 24 \times 60$ minutes 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 5 and for straddles in more detail in Table 2.

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.

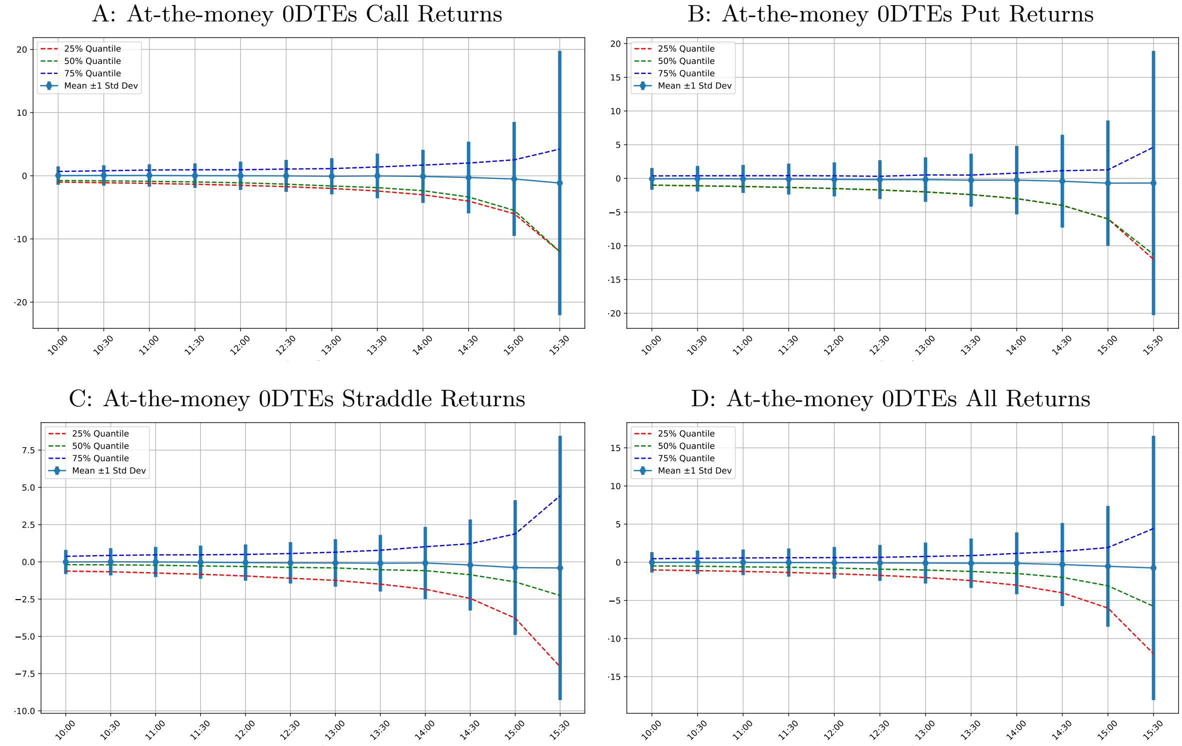

Figure 5: 0DTE Option Returns. The figure shows average returns to expiration for 0DTE SPXW options by intraday 30-minute points. At the end of each bar, we select two calls, two puts and two straddles with the strikes closest to the current SPX level, from both sides. We compute their holding returns 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.

Table 2 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. As such, demand for 0DTEs options could be rationalized by retail investors' lottery-type preferences. Therefore, 0DTEs do not stand out relative to other

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 2: 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.

maturity buckets in terms of their risk-return trade-off, though they certainly have very distinct risk characteristics and, respectively, return profiles.

4 0DTE Trading as a Risk Factor

An important question we explore next is whether the increasing appetite for 0DTEs trading and the related risks of holding these options are massive enough to affect the underlying markets through delta-hedging after sudden and large market moves, thereby posing a systemic risk to the market. Such a scenario has been alluded to in numerous media releases, some of which were co-authored by large market participants. Section 4.1 analyzes trading volumes in underlying markets and 0DTEs and their link to large returns through the (potential) delta-hedging activity and the resulting trading flows. Section 4.2 checks whether the aggregate open interest in 0DTE options contributes to propagating overnight volatility and analyzes the link between the aggregate 0DTE open interest gamma at market open and subsequent realized variance and ex post variance risk premium.[13]

4.1 Trading Activity

We examine how trading activities in the 0DTEs and underlying markets are related to realized price movements of the underlying over intraday time intervals. We are interested in whether a shock to 0DTE trading volume propagates the return volatility of the underlying and whether such propagation is more pronounced in recent years and in states with high 0DTE open interest and trading volume. Because trading volumes in underlying markets and options are interrelated and both are 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 (e.g., Pesaran 2015 and Wiesen and Beaumont 2023).

For the underlying, we use intraday 1-minute bar data for the most actively exchange-traded fund, SPY, and the front contract of the S&P500 E-mini Futures, ES. For the frequency $\xi = 1$ minute, at the end of each bar within the regular day session (from 9:31 to 16:00), we add up dollar trading volume $V_j^{\$}$ for $j =$ SPY or ES over the last minute to obtain aggregate volume $V_{d:t,\xi}^{\$}$, then convert it to log $v_{d:t,\xi}^{\$} = \ln V_{d:t,\xi}^{\$}$. For the volume of 0DTE options, we proceed in the same way, adding up for each bar the dollar-delta volumes for SPY and SPX options over the last minute and then convert it to log volume $v_{d:t,\xi}^{\$\Delta} = \ln V_{d:t,\xi}^{\$\Delta}$. We also compute simple SPY returns $R_{d:t,\xi}$ over the matching time intervals and then define a proxy for realized return volatility as the normalized absolute return $RelVol_{d:t,\xi} = |R_{d:t,\xi}|/\sigma_{d,\xi})$, where $\sigma_{d,\xi}$ is the daily

[13] Section 4.1 uses transaction-based options data. Section 4.2 uses for analysis 30-minute bars.

volatility of intraday returns on day d. For stationarity, we use the first differences of the volume variables for estimation, and also normalize them each day to unit variance.

Because we want to focus on the intraday association of the variables, we estimate their joint dynamics each day, compute the generalized impulse response functions, and finally 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 a relatively slow 0DTE market development, and 2020-2023, during which 0DTE trading volumes continuously exploded. As expected, the trading volumes for 0DTEs and the underlying are reasonably 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 absolute return and volume variables are initially higher for the underlying market than for 0DTEs (0.22 vs. 0.12). However, in the latter period, both correlations almost perfectly align at the level of 0.21-0.22.

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

$$\begin{aligned}
RelVol_{d:t,\xi} &= c_0 + \sum_{l=1}^{n} c_{1,l} \Delta v^{\$}_{d:t-l,\xi} + \sum_{l=1}^{n} c_{2,l} \Delta v^{\$\Delta}_{d:t-l,\xi} + \sum_{l=1}^{n} c_{3,l} RelVol_{d:t-l,\xi} + e_{RelVol,d:t}, \\
\Delta v^{\$\Delta}_{d:t,\xi} &= b_0 + \sum_{l=1}^{n} b_{1,l} \Delta v^{\$}_{d:t-l,\xi} + \sum_{l=1}^{n} b_{2,l} \Delta v^{\$\Delta}_{d:t-l,\xi} + \sum_{l=1}^{n} b_{3,l} RelVol_{d:t-l,\xi} + e_{\Delta v^{\$\Delta},d:t}, \\
\Delta v^{\$}_{d:t,\xi} &= a_0 + \sum_{l=1}^{n} a_{1,l} \Delta v^{\$}_{d:t-l,\xi} + \sum_{l=1}^{n} a_{2,l} \Delta v^{\$\Delta}_{d:t-l,\xi} + \sum_{l=1}^{n} a_{3,l} RelVol_{d:t-l,\xi} + e_{\Delta v^{\$},d:t},
\end{aligned} \tag{10}$$

We use the estimation output to compute generalized impulse response functions for one-standard deviation shocks to the variables.[14] 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 and plot them in Figure 6.

[14] 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.

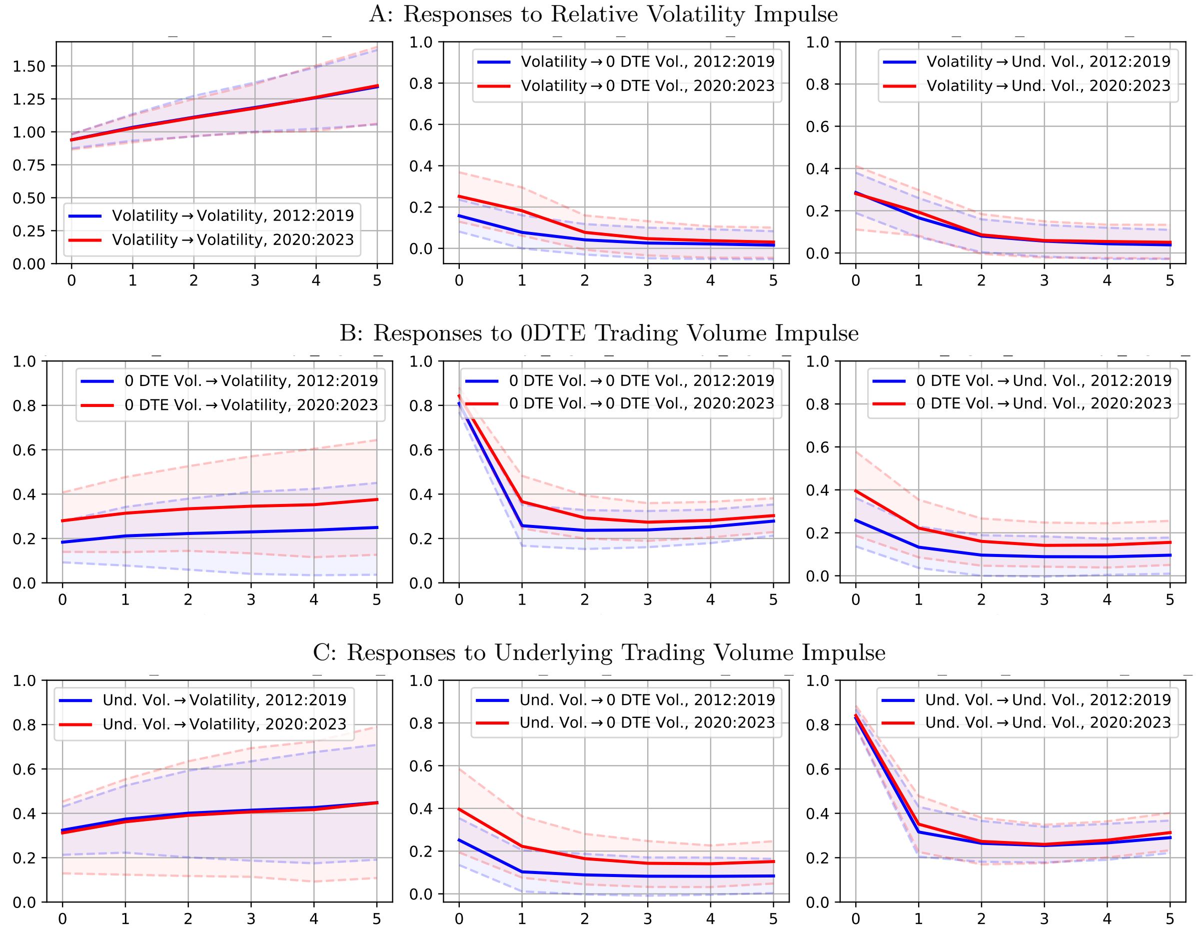

Figure 6: 0DTE Volume and Relative Volatility Cumulative Impulse Response Functions. The figure shows the average generalized impulse response functions with confidence bounds (5th and 95th percentiles of empirical daily distribution) for the VAR system in (10) estimated daily with $n = 5$ lags for $\xi = 1$ minute frequency. The averages and percentiles are computed for periods 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.

Figure 6 shows that the average response of each variable to shocks in other variables is slightly more pronounced in the later period 2020-2023 compared to 2012-2019 (the red line is always higher than the blue one in all panels). However, the differences in the response for each variable across the sub-samples are mostly economically small and not statistically significant. The propagation of market return shocks (Panel A) to future underlying return volatility and trading volume barely changes across the sub-samples, and the surge in trading dissipates quickly. 0DTE trading initially reacts strongly to the underlying return shock, which is consistent with the intuition that the applicability of delta-hedging in 0DTE markets is limited due to the high 0DTEs' gamma. Following large returns, traders often rebalance their 0DTE positions by trading 0DTEs directly, potentially dampening the intensity of delta-hedging in the underlying market.[15]

Panel B of Figure 6 depicts a more pronounced change over time for the propagation of trading shocks between 0DTE and underlying markets and the propagation of the own shock to 0DTE trading. This result tends to suggest that the markets became more integrated over time. At the same time, the impact of own shocks on underlying trading is unchanged over time, and the observed stronger link between the markets stems from the 0DTE market growth. Most importantly, these structural market changes have resulted in a stronger immediate response of the underlying absolute return to 0DTE trading shocks (Panel B, left) in recent years. Following a standard deviation shock to 0DTE trading, the underlying index variance rises from about 0.2 standard deviation in the 2012-2019 sub-period to 0.3 standard deviation in 2020-2023. Although these numbers imply a 1.5 times stronger response in the latter period, the magnitude is negligible economically — roughly 0.1 standard deviations higher absolute return.

We cannot draw statistical inference about the significance of the impulse response intensity dynamics based on just the overlap of the confidence bounds. To see formally whether the propagation of the shocks to volatility and both 0DTE and underlying trading volumes is related to 0DTE trading activity, we relate each 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 variables for considerable (more than one standard deviation) jumps of open interest dollar gamma and 0DTEs trading volume relative their past averages.[16] The results of the regressions are shown in Table 3. Neither high open interest

[15]For example, see the discussion in Episode 275 of Systematic Investor Podcast at www.toptradersunplugged.com/podcasts/systematic-investor.

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

Impulse	Rel.Vol.			0DTE Vol.			Und.Vol.		
Propagation	Rel.Vol.	0DTE Vol.	Und.Vol.	Rel.Vol.	0DTE Vol.	Und.Vol.	Rel.Vol.	0DTE Vol.	Und.Vol.
$High\ OI_d^{\$\Gamma}$	0.028**	-0.000	0.003	0.008	-0.001	-0.001	0.016	-0.003	0.003
	(2.494)	(-0.020)	(0.942)	(0.846)	(-0.352)	(-0.171)	(1.374)	(-0.743)	(1.002)
$High\ \ln Vol_d^{\$\Delta}$	-0.007	-0.003	0.001	0.008	0.004	0.008**	0.012	0.006	0.005
	(-0.527)	(-1.027)	(0.160)	(0.791)	(1.143)	(2.345)	(0.999)	(1.560)	(1.452)
$\ln RV_d^{on}$	-0.025***	-0.005***	-0.005***	-0.011***	-0.000	-0.004***	-0.020***	-0.005***	-0.003**
	(-5.225)	(-4.034)	(-3.984)	(-2.852)	(-0.015)	(-2.793)	(-4.583)	(-3.996)	(-2.434)
$\ln RV_d^{day}$	-0.004	0.009***	0.006***	-0.013**	0.004	-0.002	-0.026***	0.005**	0.000
	(-0.570)	(4.974)	(2.923)	(-2.159)	(1.590)	(-1.008)	(-3.240)	(2.269)	(0.186)
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.	0.102	0.071	0.035	0.264	0.123	0.358	0.102	0.413	0.100
Obs.	1,427	1,427	1,427	1,427	1,427	1,427	1,427	1,427	1,427

Table 3: 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 (10) that is estimated daily using 1-minute data for Relative Volatility (Rel.Vol.), 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 ($\ln RV_r^{on}$), 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 the rolling-window averages of open interest gamma and 0DTE dollar delta volume, respectively. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

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.[17] 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.[18]

To see whether the time trend in impulse response intensity is specific to the 0DTEs, we re-estimate the VAR system in (10) using option volume variable for other maturity buckets, and also for the volume aggregated over all maturities up to 22 trading days. Figure 7 shows the time-series plots of the smoothed cumulative responses five steps after a shock. In Panel A,

[17] In the Online Appendix Table IA.6, 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.

[18] 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.

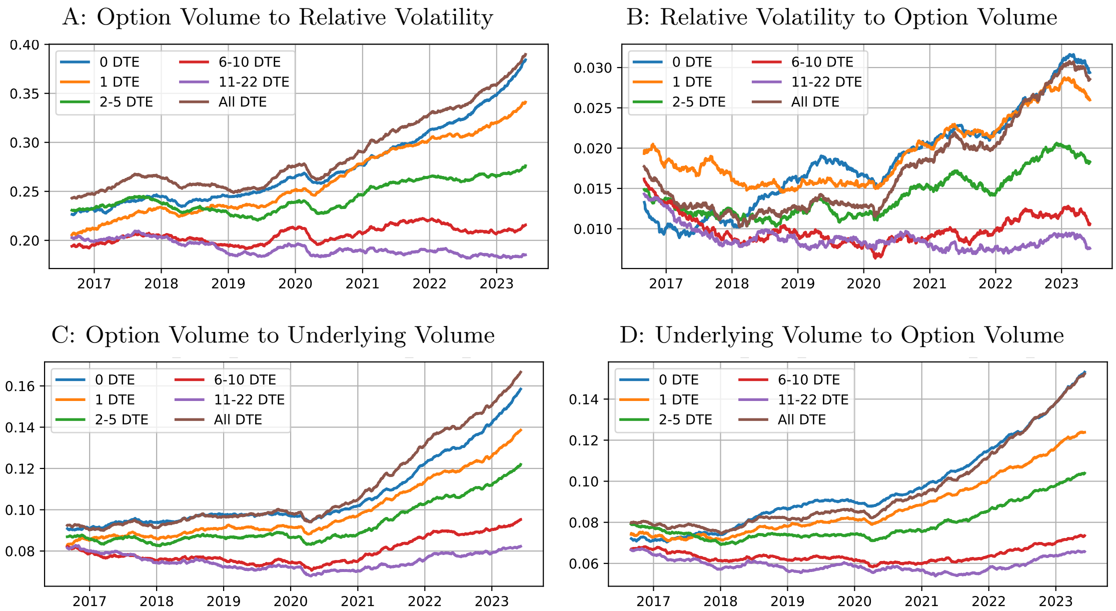

Figure 7: Dynamics of Option Volume and Relative Volatility Cumulative gIRFs. The figure shows the smoothed (exponential moving average with half life of 252 days) time-series of the cumulative generalized impulse response functions after 5 steps for the VAR system in (10) estimated each day for $\xi = 1$ minute frequency with $n = 5$ lags, separately for option volume in different maturity buckets. The variables are normalized to unit standard deviation every day, 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.

we observe a stronger response of volatility to short-term 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 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.

One potential criticism of the VAR approach, even when estimated daily, is that it recovers the average connections among variables, and we are specifically interested in outliers represented by rare events of high 0DTE trading volume and the subsequent directional moves in the underlying markets. We complement the evidence above by analyzing such intraday events, which we identify by 0DTE log volume ($\Delta v^{\$\Delta}$) jumps larger than three times its standard deviation on a given day. We are interested in the accumulation of realized returns in either the positive or negative direction following the volume jump, with the negative one having stronger implications for market stability. High volume is often associated with high return volatility, but we want to understand whether sharp jumps in 0DTE volume typically precede and potentially cause large underlying returns. We use the 5-minute cumulative returns (from $\tau + 1$ to $\tau + 5$) as a measure of market reaction to option volume shock at time τ, and test whether the market reaction differs conditional on having experienced a large 0DTE volume jump and not, and whether it depends on the realized return before and during the 0DTE trading volume jump.

Figure 8 plots the distributions of the 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 return realizations, and 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 recent debates in the media claiming that significant underlying market moves can be propagated through 0DTE trading, especially in recent years.

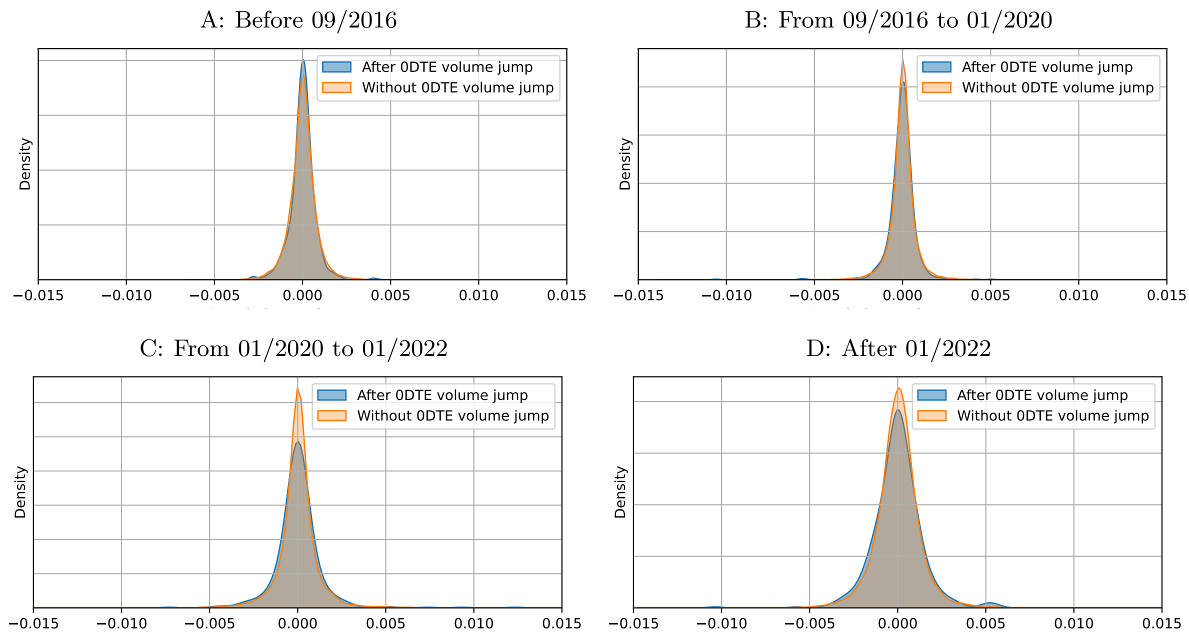

Figure 8: Cumulative Returns Conditional on 0DTE Volume Jump. The figure shows the distributions of 5-minute cumulative returns (from $\tau+1$ to $\tau+5$) conditional on having a large jump in 0DTE volume at τ and not having such a jump, for four sub-periods. We sample non-overlapping observations, skipping at least five minutes between each selected τ point. The sample period is from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration.

Table 4 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 Kolmogorov-Smirnov) it puts more weight on the tails of the distributions. Table 5 presents 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 all triple interactions in the regression and concentrate on analyzing the ones that include past cumulative return and 0DTE

	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 4: 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 $\tau + 1$ to $\tau + 5$) conditional on having a large jump in 0DTE volume at τ and not having such a jump, for four sub-periods. We sample non-overlapping observations, skipping at least five minutes between each selected τ point. The sample period is from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration.

volume jump, with and without year dummy interaction. For brevity, we do not report some interaction terms that are not central to our analysis in the table. In all the cases, we reject the 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 on the link between 0DTE volume jump and both negative and positive future returns (Q10 and Q90), but future large returns are not related to the 0DTE activity conditional on past returns, i.e., we do not find evidence for the *propagation* of realized market moves by 0DTE trading.

4.2 Variance Propagation Through Gamma Risk

A fundamental mechanism through which a rapidly increasing 0DTE aggregate exposure can affect the underlying markets is managing gamma risk, i.e., delta-hedging following large returns in the underlying market index. We build on the preceding analysis and investigate whether the burgeoning 0DTE market presents novel risks through this channel by examining how overnight and last-day intraday volatility of the underlying index propagates to the next day's realized volatility conditional on the open interest (in terms of dollar gamma) in 0DTEs in the morning.

For the first test we use log realized variance $\ln RV_d^{day}$ computed as defined in equation (3) using index returns (assuming that SPX and SPY are substitutes), the open interest dollar gamma $OI_{d,dte}^{\$\Gamma}$ computed from equation (8) using the open interest at market open and both option gammas and underlying prices reported at 10:00, aggregated for the pre-defined DTE

	Q1	Q5	Q10	Q90	Q95	Q99
0DTE Volume Jump	-0.007	0.001	0.002	-0.010*	-0.019**	-0.037
	(-0.282)	(0.076)	(0.410)	(-1.916)	(-2.228)	(-1.525)
Past Return	1.950	1.044	1.090	-6.213***	-6.193**	-4.226
	(0.172)	(0.313)	(0.597)	(-3.852)	(-2.045)	(-0.347)
0DTE Volume Jump × Past Return	-51.607	-4.357	-0.776	24.122	24.811	17.382
	(-0.477)	(-0.184)	(-0.062)	(1.518)	(0.764)	(0.141)
0DTE Volume Jump × Year 2021	0.011	-0.003	0.010	0.016	0.031	0.017
	(0.183)	(-0.156)	(0.715)	(1.235)	(1.467)	(0.231)
0DTE Volume Jump × Year 2022	-0.008	-0.002	-0.002	0.004	0.009	0.157***
	(-0.161)	(-0.096)	(-0.133)	(0.374)	(0.513)	(2.734)
0DTE Volume Jump × Year 2023	-0.005	-0.053**	-0.036**	0.040**	0.090***	0.152*
	(-0.070)	(-1.988)	(-2.137)	(2.534)	(3.418)	(1.903)
Past Return × 0DTE Volume Jump × Year 2021	82.265	10.533	-3.995	-21.647	-33.479	-25.417
	(0.309)	(0.304)	(-0.153)	(-0.713)	(-0.511)	(-0.070)
Past Return × 0DTE Volume Jump × Year 2022	66.997	3.583	13.683	-17.698	-22.067	4.772
	(0.597)	(0.133)	(0.907)	(-1.005)	(-0.641)	(0.037)
Past Return × 0DTE Volume Jump × Year 2023	78.544	18.195	1.174	-6.632	13.700	38.228
	(0.604)	(0.430)	(0.052)	(-0.290)	(0.345)	(0.272)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	84,645	84,645	84,645	84,645	84,645	84,645

Table 5: 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 $\tau+1$ to $\tau+5$ on the dummy for the 0DTE Volume Jump at τ, past five-minute cumulative return from $\tau-4$ to τ (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 τ point. The sample period is from 01/2012 to 14/06/2023 and includes only days with 0DTE expiration.

buckets and for both SPXW and SPY options, to capture total rebalancing risk due to fluctuations in the underlying market index. Then we estimate the regression

$$\ln RV_d^{day} = b_0 + OI_{dte,d}^{\$\Gamma}(b_1 + b_2 \ln RV_d^{on} + b_3 \ln RV_{d-1}^{day}) + \mathbf{CX} + \varepsilon_d, \tag{11}$$

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.[19] We standardize the dollar gamma levels for each DTE bucket to unit variance to make coefficients comparable.

Table 6 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 variance interaction

[19] 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.

	$\ln RV_d^{day}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI_{dte,d}^{\$\Gamma} \times \ln RV_d^{on}$	0.014	-0.165*	-0.006	-0.104*	-0.136**
	(0.193)	(-1.927)	(-0.112)	(-1.716)	(-2.050)
$OI_{dte,d}^{\$\Gamma} \times \ln RV_{d-1}^{day}$	-0.161	-0.125	-0.228*	-0.284**	-0.079
	(-0.848)	(-0.668)	(-1.784)	(-2.218)	(-0.588)
$OI_{dte,d}^{\$\Gamma}$	-2.295	-3.395*	-3.417**	-5.122***	-2.668*
	(-1.238)	(-1.932)	(-2.484)	(-3.612)	(-1.893)
$\ln RV_d^{on}$	0.019	0.029**	0.019**	0.033***	0.039***
	(1.345)	(2.246)	(1.962)	(3.276)	(3.546)
$\ln RV_{d-1}^{day}$	0.568***	0.562***	0.571***	0.584***	0.563***
	(15.038)	(15.935)	(19.254)	(20.312)	(18.564)
$\ln RV_{d-2}^{day}$	0.129***	0.181***	0.130***	0.140***	0.143***
	(4.223)	(5.569)	(5.605)	(5.932)	(6.034)
$\ln RV_{d-3}^{day}$	0.017	0.016	0.021	0.014	0.019
	(0.527)	(0.530)	(0.932)	(0.626)	(0.832)
$\ln RV_{d-4}^{day}$	0.064*	0.041	0.053**	0.048**	0.051**
	(1.956)	(1.457)	(2.322)	(2.162)	(2.277)
$\ln RV_{d-5}^{day}$	0.022	0.041	0.036*	0.044**	0.046**
	(0.856)	(1.487)	(1.818)	(2.249)	(2.369)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.748	0.751	0.728	0.725	0.721
Obs.	1,440	1,431	2,652	2,755	2,786

Table 6: Volatility Propagation. 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 (11). 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. Dollar gamma levels are standardized to unit variance then divided by 10. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

terms are linked to a lower variance the next day. Moreover, open interest gamma in the morning of day d is mostly *negatively* related to the intraday volatility, and the coefficient is significant for all buckets beyond 0DTEs.

There are several interpretations of the chain of events compatible with this evidence. First, *delta-hedgers* on the market are predominantly *long volatility*, and hence, long gamma. High gamma levels lead to a more intense delta-hedging by gamma buyers, dampening the price swings: traders with long gamma positions would need to sell after the underlying price goes up and buy after the price goes down. Second, in anticipation of lower realized intraday volatility, the price of volatility (and hence, option premiums) decreases, and overall open interest increases, reflecting a higher demand at the new price.[20] Overall, we do not find evidence for higher open interest gamma levels destabilizing prices and contributing to clustered volatility shocks.

Overall, we find evidence that 0DTEs trading is linked to the underlying index return variance. The pattern has intensified significantly in the more recent periods over which 0DTEs trading surged. However, the pattern is not caused by day-to-day levels of 0DTE trading volume and open interest gamma at market open. The the economic magnitude of the observed increase in the shock propagation in recent periods is quite small. More importantly, we find no supportive evidence for the claims that 0DTE volume surges propagate negative intraday market moves, which would be consistent with 0DTE trading making markets more fragile.

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 2 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 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).

[20] For a more detailed causal analysis, one would benefit from an intraday composition of open interest by types of traders, but this data is unavailable so far.

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.[21]

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

$$Vol^{\$\Delta}_{dte,d:t} = b_0 + b_1 \mathbb{1}(\textit{Before FOMC})_{d:t} + b_2 \mathbb{1}(\textit{After FOMC})_{d:t} + \mathbf{CX} + \varepsilon_{d:t}. \quad (12)$$

$Vol^{\$\Delta}_{dte,d:t}$ 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 (9), $\mathbb{1}(\textit{Before FOMC})_{d:t}$ 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 9 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,

[21]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.

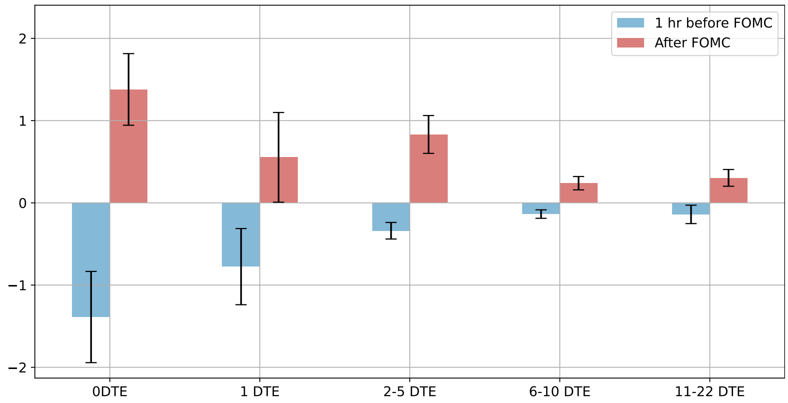

Figure 9: Option Trading Volume Around FOMC Announcement by DTE. This Figure reports the coefficient estimates and the 95% confidence bounds from regressing dollar delta volume (in billions) at a 30-minute frequency on indicator variables for periods around FOMC announcements, as specified in equation (12). 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.

with 0DTEs volume decrease and subsequent increase before and after FOMC being almost twice larger compared to other buckets.

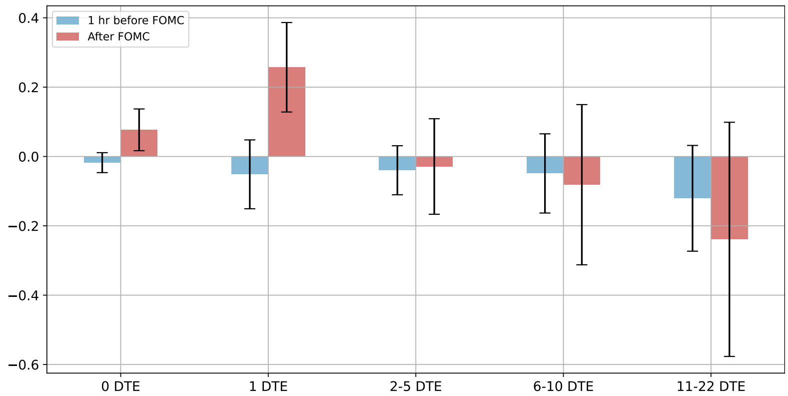

Figure 10: Realized VRP Around FOMC Announcement by DTE. This Figure reports coefficient estimates and the 95% confidence intervals from regressing the realized variance risk premium (VRP^{Δ} in % p.a.) for each intraday 30-minute bar on indicator variables for periods around FOMC announcements based on a version of equation (12) 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 (5) for a DTE bucket dte (i.e., $VRP^{\$\Delta}_{dte,d:t,30m}$) on the left-hand side of equation (12). Figure 10 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.

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 11) and realized VRPs (Figure 12) on FOMC days. There is a clear reduction in trading before the FOMC decision announcement and a spike afterward.[22] 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 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.[23]

[22]The other DTE buckets demonstrate similar changes in trading patterns consistent with results in Figure 9.
[23]In unreported results, we do not observe any significant changes in realized VRP for longer-term options.

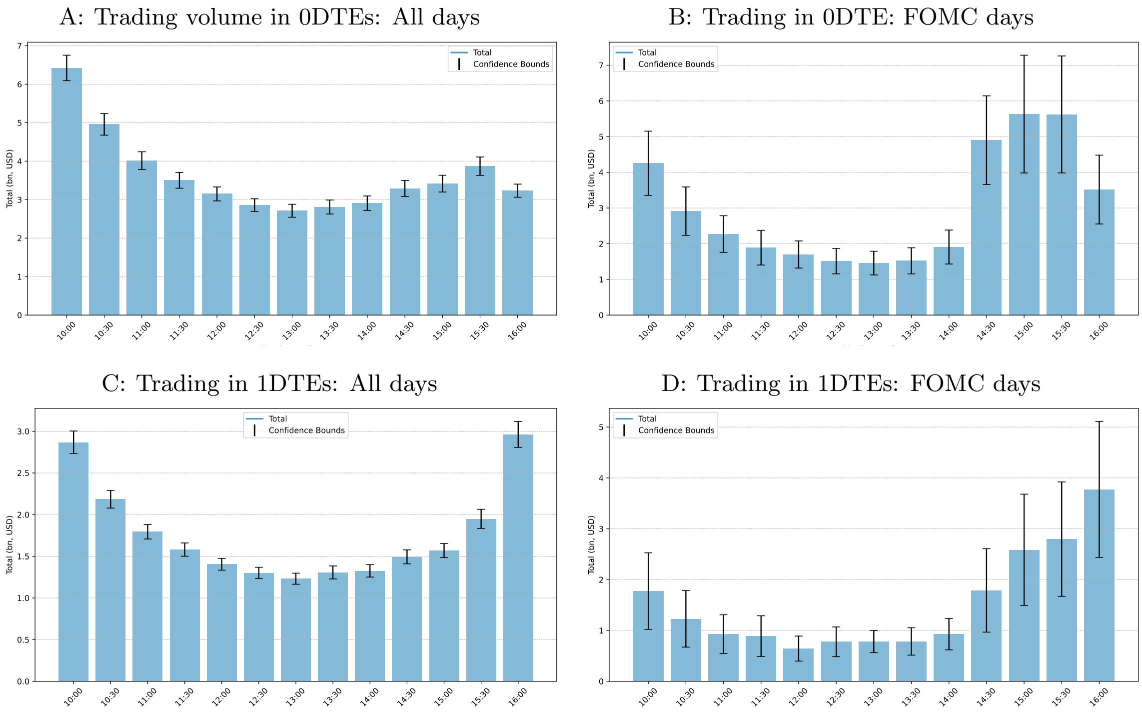

Figure 11: Trading Volume by DTEs and Intraday Bars: FOMC Effect. This Figure reports average trading volume (in terms of dollar delta) for SPXW and SPY options, separately for 0- and 1DTEs, and the 95% confidence intervals for each intraday 30-minute bar for all days in the sample and for days with 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.

6 Robustness and Extensions

We conduct a number of tests to assess the robustness of our findings and reconcile some of our results with the existing literature.

We see in Figure IA.1 that the intraday variance risk premium to expiry is slightly higher in the 2020-2023 period compared to 2012-2019 with lower 0DTE trading volumes. However, the pattern does not have much effect on the distribution of realized returns of 0DTE straddles shown in Figure IA.2.

Splitting the sample into periods with low and high 0DTE trading volume does not change the main inferences of our analysis on propagation of volatility by open interest gamma in 0DTEs—the results for 2012-2019 and 2020-2023 can be seen in Tables IA.1 and IA.2.

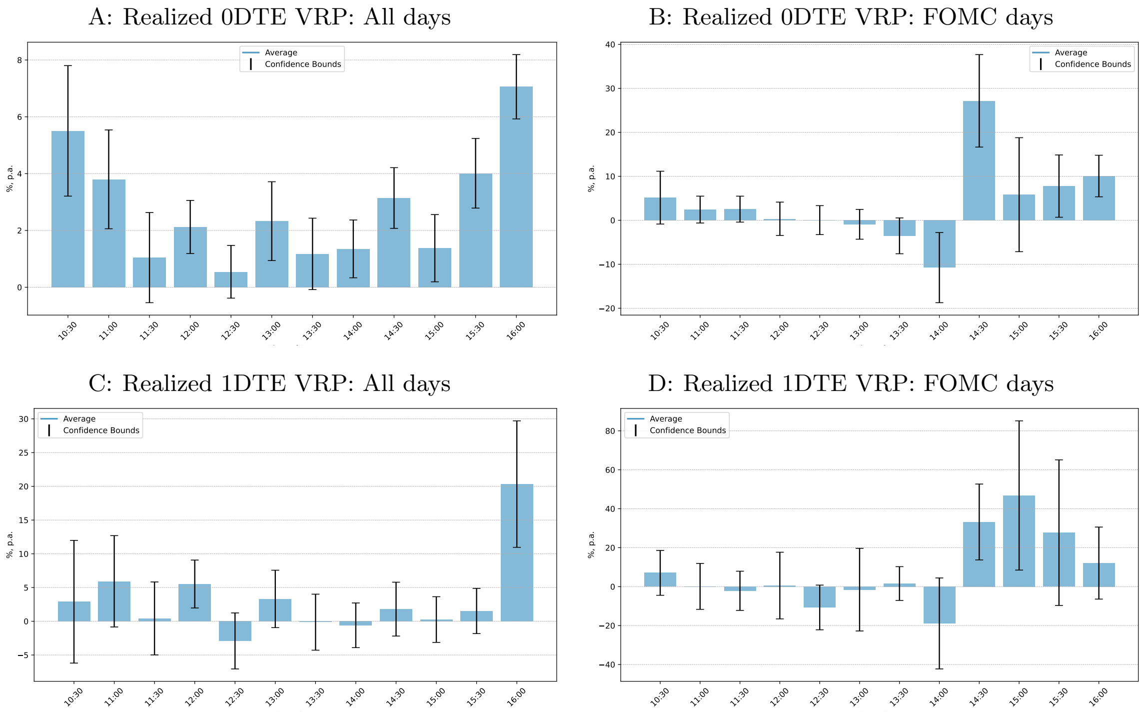

Figure 12: Realized VRP by DTEs and Intraday Bars: FOMC Effect. This Figure reports average realized ex post VRP^{Δ} (in % p.a.) for SPXW options, separately for 0- and 1DTEs, and the 95% confidence intervals for each intraday 30-minute bar for all days in the sample and for days with FOMC announcements, 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.

Appendix Section IA.1.3 provides the analysis of the link between realized variance risk premium and open interest gamma.

Table IA.6 extends the analysis of the conditional generalized IRFs by including interactions of gamma and volume variables with year dummies, and does not show any significantly stronger association between high open interest and trading volume and the propagation 0DTE Volume shocks in more recent periods.

Appendix Section IA.1.4 gives the analysis of the discrepancies between our results and findings of the positive effect of 0DTE trading volume on the underlying variance documented in Brogaard, Han, and Won (2023).

7 Conclusion

Following the introduction of weekly options with a daily expiration cycle by Cboe and a surge in popularity of ultra-short maturity options in recent years, daily trading volumes in zero days to expiration options (0DTEs) increased more than tenfold from its 2012 level. As a result, several large market participants have weighed-in on the ballooning 0DTEs trading, suggesting that 0DTE trading creates systemic risks for the underlying markets due to delta-hedging flows that can trail large and sudden market moves.

We analyze the recent surge in trading volumes for 0DTEs and other maturity buckets (from one to 22 trading days to expiration) and its implications for the broader market. We find no evidence that delta-hedging in 0DTEs has a destabilizing impact on the underlying market. The sharp rise in trading volume for 0DTE options has not been matched by a commensurate increase in open interest, indicating that a significant portion of the trading is intraday and may not carry over to the next trading session. Moreover, contrary to the concerns, we find that the large gamma positions in short-term S&P500 options are instead linked to lower underlying volatility, suggesting that the market impact of 0DTE options may be less about creating systemic risks and more about market participants managing their positions through hedging. In recent periods, 0DTE and underlying markets have become more connected during the day, and trading volume in either market reacts stronger to trading volume surges in the other. This structural market change has an economically small (and statistically insignificant) effect on the propagation of intraday index volatility through 0DTE trading.

0DTEs stand out from other maturities in terms of their risks and returns: these options deliver the highest realized variance risk premium (i.e., implied variance is higher than the realized one), especially close to expiration. The returns on delta-neutral 0DTE straddles are very risky and exhibit positive skewness, both most pronounced close to expiration. These features potentially rationalize long positions in 0DTEs by lottery seekers.

Ultra-short maturity options are used as bets on the resolution of uncertainty, such as the macroeconomic uncertainty before the FOMC announcements, and on market direction following FOMC decisions. Traders betting on uncertainty resolution would short volatility in 0- and 1-DTEs before the announcements, and lottery-seeking traders would buy the options before such announcements to get exposure to extreme market moves.

Overall, we do not find supportive evidence for concerns in the media that 0DTE options might be introducing systemic risks to the underlying market. Instead, our analysis suggests that these options serve specific strategic purposes for traders without necessarily destabilizing the market. Future studies could assess the longer-term effects of 0DTE options trading on market stability and whether market participants' behaviors evolve in a way that could pose systemic risks over time. Such an analysis would require the history of intraday open interest in options of various maturities disaggregated across market participant types.

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A Additional Tables

	Count	Mean	StDev	Min	25%	50%	75%	Max
0 DTE								
Trade Volume (USD, bn)	1433	192.6	204.9	4.1	40.3	89.7	303.8	854.4
Trade Volume Delta (USD, bn)	1433	47.0	49.6	1.3	11.8	23.4	71.2	227.1
Open Interest (USD, bn)	1433	163.2	111.8	11.3	78.8	133.1	216.5	720.7
Open Interest Delta (USD, bn)	1433	3.1	18.9	-135.4	-3.8	2.9	11.3	106.6
Open Interest Gamma (USD, bn)	1433	1376.0	900.9	7.0	714.4	1173.6	1776.1	7245.7
1 DTE								
Trade Volume (USD, bn)	1429	91.2	75.3	2.9	34.3	62.6	136.8	444.4
Trade Volume Delta (USD, bn)	1429	22.9	19.9	0.8	8.1	15.5	33.4	124.5
Open Interest (USD, bn)	1429	139.9	109.5	7.4	57.8	99.2	201.2	674.1
Open Interest Delta (USD, bn)	1429	2.9	18.0	-123.3	-2.8	2.2	8.9	98.9
Open Interest Gamma (USD, bn)	1429	1018.4	870.2	48.7	443.7	788.1	1337.3	16521.1
2-5 DTE								
Trade Volume (USD, bn)	2643	73.9	60.5	3.0	29.8	55.6	95.8	435.6
Trade Volume Delta (USD, bn)	2643	16.3	13.3	0.5	6.9	11.7	21.1	98.0
Open Interest (USD, bn)	2643	128.8	98.3	4.2	51.8	96.5	190.0	655.9
Open Interest Delta (USD, bn)	2643	2.6	16.4	-116.8	-3.1	2.0	8.2	97.9
Open Interest Gamma (USD, bn)	2643	857.5	662.4	28.0	365.7	681.0	1163.8	8020.8
6-10 DTE								
Trade Volume (USD, bn)	2734	33.2	22.0	0.8	16.6	28.4	45.2	167.8
Trade Volume Delta (USD, bn)	2734	7.5	5.2	0.1	3.7	6.2	10.2	36.8
Open Interest (USD, bn)	2734	88.7	80.6	3.9	26.5	57.5	130.2	555.2
Open Interest Delta (USD, bn)	2734	1.5	12.9	-99.6	-2.0	1.0	5.0	98.2
Open Interest Gamma (USD, bn)	2734	517.2	453.9	10.7	169.4	384.6	725.7	4607.8
11-22 DTE								
Trade Volume (USD, bn)	2779	36.0	24.3	0.5	16.8	32.0	49.6	148.9
Trade Volume Delta (USD, bn)	2779	8.6	6.0	0.1	4.1	7.3	11.5	43.9
Open Interest (USD, bn)	2779	73.3	74.5	0.6	15.9	44.9	107.4	578.5
Open Interest Delta (USD, bn)	2779	0.8	10.9	-107.6	-1.4	0.5	3.0	101.0
Open Interest Gamma (USD, bn)	2779	373.2	365.4	6.7	101.1	250.1	557.2	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 (6) to (9) 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 a 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. 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 summary. The sample period is from 01/2012 to 14/06/2023.

Online Appendix

for

0DTEs: Trading, Gamma Risk and Volatility Propagation

This version: May 14, 2024

IA.1 Robustness and Extensions

IA.1.1 Variance Risk Premium and Option Returns for Subperiods

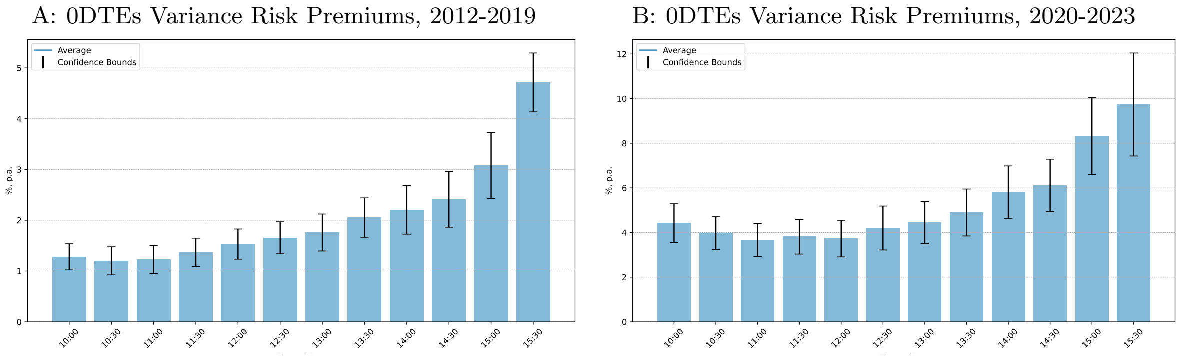

Figure IA.1: 0DTE Variance Risk Premiums by Periods. The figure shows average variance risk premiums (VRP) for SPXW options by intraday 30-minute points for 0DTEs, for two periods, from 2012 to 2019 in Panel A, and from 2020 to 2023 in Panel B. VRP is computed as implied minus realized variances to expiration at 16:00 annualized using exact minutes to expiration and $365 \times 24 \times 60$ minutes per day. 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.

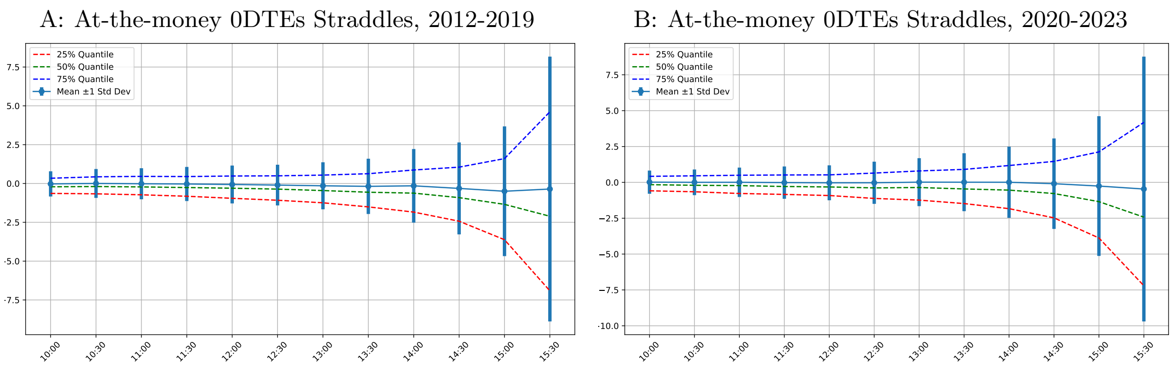

Figure IA.2: 0DTE Straddles Returns by Periods. The figure shows average returns to expiration for 0DTE SPXW straddles by intraday 30-minute points for two periods, from 2012 to 2019 in Panel A and from 2020 to 2023 in Panel B. At the end of each bar, we select two straddles with the strike closest to, from both sides, 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 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.

IA.1.2 Volatility Propagation by Open Interest Gamma for Subperiods

	$\ln RV_d^{day}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI_{dte,d}^{\$\Gamma} \times \ln RV_d^{on}$	0.052	-0.218	-0.027	-0.120	-0.130
	(0.544)	(-1.635)	(-0.382)	(-1.525)	(-1.565)
$OI_{dte,d}^{\$\Gamma} \times \ln RV_{d-1}^{day}$	-0.470**	0.181	-0.229	-0.220	-0.114
	(-2.062)	(0.620)	(-1.435)	(-1.283)	(-0.641)
$OI_{dte,d}^{\$\Gamma}$	-5.235**	-0.502	-3.949**	-4.921**	-3.069
	(-2.403)	(-0.171)	(-2.256)	(-2.485)	(-1.599)
$\ln RV_d^{on}$	0.009	0.032	0.021*	0.031***	0.034***
	(0.469)	(1.612)	(1.893)	(2.780)	(2.815)
$\ln RV_{d-1}^{day}$	0.644***	0.541***	0.580***	0.582***	0.580***
	(12.679)	(9.795)	(15.894)	(15.794)	(15.013)
$\ln RV_{d-2}^{day}$	0.049	0.158***	0.086***	0.101***	0.105***
	(1.166)	(3.197)	(2.980)	(3.337)	(3.495)
$\ln RV_{d-3}^{day}$	0.089**	0.070	0.057**	0.046*	0.053**
	(2.148)	(1.599)	(2.150)	(1.692)	(1.970)
$\ln RV_{d-4}^{day}$	0.058	0.058	0.054*	0.049*	0.050*
	(1.161)	(1.448)	(1.847)	(1.726)	(1.742)
$\ln RV_{d-5}^{day}$	-0.009	-0.016	0.016	0.032	0.030
	(-0.255)	(-0.393)	(0.621)	(1.309)	(1.212)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.658	0.678	0.652	0.646	0.640
Obs.	793	787	1,789	1,892	1,923

Table IA.1: Volatility Propagation, 2012-2019. 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 (11). 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. Dollar gamma levels are standardized to unit variance then divided by 10. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 12/2019.

	$\ln RV_d^{day}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV_d^{on}$	-0.068	-0.061	0.015	-0.081	-0.203**
	(-0.763)	(-0.596)	(0.148)	(-0.883)	(-2.223)
$OI^{\$\Gamma}_{dte,d} \times \ln RV_{d-1}^{day}$	0.212	-0.291	-0.384*	-0.616***	0.061
	(0.840)	(-1.348)	(-1.662)	(-2.946)	(0.290)
$OI^{\$\Gamma}_{dte,d}$	0.648	-4.089*	-4.304*	-7.606***	-1.832
	(0.242)	(-1.792)	(-1.839)	(-3.799)	(-0.938)
$\ln RV_d^{on}$	0.037**	0.022	0.018	0.037*	0.068***
	(1.966)	(1.355)	(0.855)	(1.821)	(2.962)
$\ln RV_{d-1}^{day}$	0.485***	0.569***	0.586***	0.635***	0.517***
	(9.182)	(12.476)	(11.180)	(12.337)	(9.228)
$\ln RV_{d-2}^{day}$	0.209***	0.209***	0.205***	0.206***	0.210***
	(4.912)	(4.910)	(5.306)	(5.481)	(5.476)
$\ln RV_{d-3}^{day}$	-0.057	-0.045	-0.042	-0.046	-0.050
	(-1.167)	(-1.043)	(-1.094)	(-1.214)	(-1.292)
$\ln RV_{d-4}^{day}$	0.066	0.010	0.040	0.037	0.048
	(1.574)	(0.255)	(1.108)	(1.046)	(1.329)
$\ln RV_{d-5}^{day}$	0.064*	0.113***	0.075**	0.076**	0.083**
	(1.770)	(3.134)	(2.344)	(2.352)	(2.568)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.711	0.711	0.714	0.717	0.713
Obs.	647	644	863	863	863

Table IA.2: Volatility Propagation, 2020-2023. 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 (11). Open interest is recorded at market open and converted to dollar gamma $OI^{\$\Gamma}_{d,dte}$ 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. Dollar gamma levels are standardized to unit variance then divided by 10. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2020 to 06/2023.

IA.1.3 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 following regression

$$VRP^{\Delta}_{dte,d} = b_0 + OI^{\$\Gamma}_{dte,d} \times (b_1 + b_2 \ln RV^{on}_d + b_3 VRP^{\Delta}_{dte,d-1}) + \mathbf{CX} + \varepsilon_d, \tag{IA.1.1}$$

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.3 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 6 and with lagged variance risk premium in Table IA.3 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.

The split of the sample into periods with low and high 0DTE trading volume (2012-2019 and 2020-2023) for the analysis of realized variance risk premium in Tables IA.4 and IA.5 shows that the full sample result is driven predominantly by the latter part of the sample period with high short-term options trading volume.

	$VRP^{\Delta}_{dte,d}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV^{on}_{d}$	0.021	-0.004	0.023	0.043	0.102
	(1.133)	(-0.272)	(0.721)	(0.855)	(1.300)
$OI^{\$\Gamma}_{dte,d} \times VRP_{d-1}$	-5.656***	-4.040***	-2.270*	0.600	-0.478
	(-3.932)	(-4.333)	(-1.959)	(0.562)	(-0.441)
$OI^{\$\Gamma}_{dte,d}$	0.310	-0.058	0.328	0.342	1.001
	(1.287)	(-0.314)	(0.735)	(0.512)	(0.930)
$\ln RV^{on}_{d}$	-0.004	0.002	-0.009	-0.015	-0.032*
	(-0.951)	(0.712)	(-1.236)	(-1.560)	(-1.752)
VRP_{d-1}	0.850***	0.574***	0.451**	-0.024	0.127
	(4.811)	(5.010)	(2.111)	(-0.161)	(0.721)
VRP_{d-2}	0.200***	0.251***	0.122	0.071	-0.044
	(3.075)	(5.502)	(1.432)	(1.172)	(-0.977)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.635	0.493	0.105	0.014	0.010
Obs.	1,363	1,353	2,424	2,504	2,710

Table IA.3: 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.1.1). 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. t-statistics (in parentheses) use Newey and West (1987) standard errors with five lags. The sample period is from 01/2012 to 14/06/2023.

	$VRP^{\Delta}_{dte,d}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV^{on}_{d}$	-0.003	-0.008	-0.032	0.019	0.116
	(-0.357)	(-0.496)	(-1.207)	(0.424)	(1.357)
$OI^{\$\Gamma}_{dte,d} \times VRP_{d-1}$	0.275	-0.338	-1.829	1.894	-0.417
	(0.246)	(-0.166)	(-0.882)	(1.321)	(-0.347)
$OI^{\$\Gamma}_{dte,d}$	-0.029	-0.126	-0.397	0.125	1.432
	(-0.249)	(-0.587)	(-1.060)	(0.209)	(1.217)
$\ln RV^{on}_{d}$	0.002	0.004	0.003	-0.003	-0.024
	(1.095)	(1.346)	(0.441)	(-0.359)	(-1.206)
VRP_{d-1}	-0.064	-0.033	0.461	-0.116	0.264
	(-0.593)	(-0.281)	(1.167)	(-0.682)	(1.325)
VRP_{d-2}	0.196*	-0.021	-0.040	0.074	-0.016
	(1.866)	(-0.341)	(-0.604)	(1.338)	(-0.248)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.075	0.008	0.061	0.040	0.050
Obs.	719	712	1,564	1,644	1,850

Table IA.4: Variance Risk Premium and Open Interest Gamma, 2012-2019. 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.1.1). 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. t-statistics (in parentheses) use Newey and West (1987) standard errors with five lags. The sample period is from 01/2012 to 12/2019.

	$VRP^{\Delta}_{dte,d}$				
	0-DTE	1-DTE	2-5 DTE	6-10 DTE	11-22 DTE
$OI^{\$\Gamma}_{dte,d} \times \ln RV^{on}_d$	0.058	-0.001	0.139*	0.112	0.125
	(1.483)	(-0.039)	(1.823)	(1.123)	(0.742)
$OI^{\$\Gamma}_{dte,d} \times VRP_{d-1}$	-6.112***	-3.586***	-1.983*	-0.596	-0.439
	(-4.467)	(-4.426)	(-1.862)	(-0.703)	(-0.428)
$OI^{\$\Gamma}_{dte,d}$	0.756	-0.025	1.632*	1.045	0.872
	(1.579)	(-0.104)	(1.677)	(0.809)	(0.393)
$\ln RV^{on}_d$	-0.013	-0.000	-0.038**	-0.048*	-0.063
	(-1.461)	(-0.091)	(-2.156)	(-1.798)	(-1.410)
VRP_{d-1}	0.901***	0.620***	0.370*	0.073	0.012
	(5.475)	(5.592)	(1.828)	(0.398)	(0.056)
VRP_{d-2}	0.160**	0.245***	0.234***	0.050	-0.104
	(2.369)	(4.683)	(2.746)	(0.585)	(-1.524)
Year Dummies	Yes	Yes	Yes	Yes	Yes
R-squared Adj.	0.678	0.583	0.176	0.014	0.015
Obs.	642	639	858	858	858

Table IA.5: Variance Risk Premium and Open Interest Gamma, 2020-2023. 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.1.1). 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. t-statistics (in parentheses) use Newey and West (1987) standard errors with five lags. The sample period is from 01/2020 to 06/2023.

IA.1.4 Analysis of the generalized Impulse Response Functions

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 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 $OI_d^{\$\Gamma}$, 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 options for the same underlying maturing within the next month, denoted $DTE0\%$.[24] 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.7 are consistent with our inferences after accounting for the above-mentioned controls.

[24]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.

Impulse	Abs.Ret.			0DTE Vol.			Und.Vol.		
Propagation	Abs.Ret.	0DTE Vol.	Und.Vol.	Abs.Ret.	0DTE Vol.	Und.Vol.	Abs.Ret.	0DTE Vol.	Und.Vol.
$High\ OI_d^{\$\Gamma}$	-0.127***	0.012*	0.003	-0.075	0.001	0.003	-0.011	0.021	0.021
	(-4.040)	(1.831)	(0.386)	(-1.102)	(0.076)	(0.159)	(-0.403)	(1.130)	(1.428)
$High\ \ln Vol_d^{\$\Delta}$	-0.001	0.017*	-0.017	-0.007	0.017	0.030***	-0.037	0.015	0.001
	(-0.047)	(1.830)	(-1.562)	(-0.141)	(0.993)	(2.846)	(-0.824)	(0.841)	(0.061)
$\ln RV_d^{on}$	-0.026***	-0.005***	-0.005***	-0.011***	-0.000	-0.004***	-0.020***	-0.005***	-0.003**
	(-5.539)	(-4.188)	(-3.949)	(-2.847)	(-0.039)	(-2.660)	(-4.474)	(-3.981)	(-2.296)
$\ln RV_d^{day}$	-0.002	0.009***	0.006***	-0.012*	0.004*	-0.002	-0.025***	0.004**	0.000
	(-0.294)	(4.910)	(3.147)	(-1.954)	(1.701)	(-1.059)	(-3.239)	(2.204)	(0.238)
$High\ OI_d^{\$\Gamma} \times Year\ 2013$	0.189***	0.001	-0.009	0.076	-0.014	-0.017	0.016	-0.023	-0.013
	(3.458)	(0.055)	(-0.577)	(1.082)	(-0.838)	(-0.846)	(0.410)	(-1.091)	(-0.759)
$High\ OI_d^{\$\Gamma} \times Year\ 2014$	0.157***	-0.015	0.011	0.064	0.012	0.007	0.083*	-0.008	-0.020
	(3.009)	(-0.902)	(0.765)	(0.843)	(0.699)	(0.286)	(1.646)	(-0.317)	(-0.995)
$High\ OI_d^{\$\Gamma} \times Year\ 2015$	0.251***	-0.012	0.044***	0.197***	0.015	0.043**	0.027	-0.040	-0.001
	(4.282)	(-0.742)	(3.757)	(2.646)	(0.926)	(2.128)	(0.582)	(-1.640)	(-0.061)
$High\ OI_d^{\$\Gamma} \times Year\ 2016$	0.104*	-0.031**	-0.001	0.152**	-0.004	0.009	0.063	-0.010	0.001
	(1.775)	(-2.218)	(-0.065)	(1.977)	(-0.273)	(0.441)	(1.189)	(-0.436)	(0.069)
$High\ OI_d^{\$\Gamma} \times Year\ 2017$	0.134***	-0.014	-0.011	0.039	-0.017	-0.016	0.018	-0.025	-0.030*
	(3.236)	(-1.240)	(-0.763)	(0.541)	(-1.227)	(-0.845)	(0.474)	(-1.209)	(-1.805)
$High\ OI_d^{\$\Gamma} \times Year\ 2018$	0.181***	-0.019**	-0.007	0.097	-0.002	-0.004	0.074*	-0.026	-0.025
	(3.963)	(-1.984)	(-0.561)	(1.369)	(-0.122)	(-0.183)	(1.780)	(-1.233)	(-1.358)
$High\ OI_d^{\$\Gamma} \times Year\ 2019$	0.198***	-0.009	0.010	0.084	-0.004	-0.022	0.028	-0.038*	-0.020
	(4.594)	(-0.781)	(0.799)	(1.176)	(-0.337)	(-1.190)	(0.621)	(-1.819)	(-1.154)
$High\ OI_d^{\$\Gamma} \times Year\ 2020$	0.114***	-0.004	0.005	0.063	0.002	0.018	0.037	-0.010	-0.013
	(2.621)	(-0.357)	(0.387)	(0.880)	(0.146)	(0.943)	(0.895)	(-0.492)	(-0.737)
$High\ OI_d^{\$\Gamma} \times Year\ 2021$	0.177***	-0.011	0.010	0.087	0.002	-0.018	-0.000	-0.039*	-0.018
	(4.200)	(-1.031)	(0.655)	(1.189)	(0.123)	(-0.859)	(-0.002)	(-1.862)	(-1.016)
$High\ OI_d^{\$\Gamma} \times Year\ 2022$	0.153***	-0.019*	-0.006	0.078	0.004	0.007	0.003	-0.010	-0.020
	(3.533)	(-1.956)	(-0.470)	(1.053)	(0.293)	(0.381)	(0.056)	(-0.479)	(-1.098)
$High\ OI_d^{\$\Gamma} \times Year\ 2023$	0.093	-0.010	-0.024	0.062	0.001	-0.017	-0.010	-0.025	-0.025
	(1.584)	(-0.813)	(-1.353)	(0.866)	(0.037)	(-0.909)	(-0.191)	(-1.099)	(-1.309)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2013$	0.229***	0.012	0.058***	0.058	-0.042	-0.014	0.188**	-0.002	0.046
	(2.643)	(0.692)	(2.627)	(0.703)	(-1.282)	(-0.688)	(1.983)	(-0.089)	(1.153)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2014$	-0.059	-0.021	0.021	-0.002	-0.021	-0.016	0.007	-0.013	-0.008
	(-0.953)	(-1.118)	(1.231)	(-0.032)	(-0.904)	(-0.914)	(0.119)	(-0.641)	(-0.414)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2015$	-0.017	-0.022	0.022	-0.037	0.001	-0.003	0.052	0.009	0.006
	(-0.261)	(-1.411)	(0.850)	(-0.599)	(0.065)	(-0.177)	(0.956)	(0.417)	(0.268)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2016$	0.053	-0.004	0.021	-0.005	-0.021	-0.018	0.019	-0.009	0.004
	(0.959)	(-0.312)	(1.302)	(-0.086)	(-1.042)	(-1.059)	(0.277)	(-0.436)	(0.209)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2017$	0.056	-0.019*	0.026*	0.051	-0.018	-0.024	0.105*	-0.009	0.013
	(1.218)	(-1.665)	(1.745)	(0.998)	(-0.985)	(-1.548)	(1.940)	(-0.427)	(0.805)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2018$	-0.059	-0.022*	0.028**	0.016	-0.020	-0.020	0.054	0.003	0.012
	(-1.373)	(-1.886)	(2.084)	(0.309)	(-1.099)	(-1.415)	(1.025)	(0.145)	(0.687)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2019$	0.030	-0.026*	0.002	0.066	-0.016	-0.001	0.090	-0.008	-0.002
	(0.640)	(-1.884)	(0.111)	(1.146)	(-0.846)	(-0.056)	(1.589)	(-0.400)	(-0.116)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2020$	-0.014	-0.035***	0.012	0.011	-0.010	-0.031**	0.067	-0.024	-0.002
	(-0.301)	(-2.954)	(0.864)	(0.213)	(-0.527)	(-2.292)	(1.201)	(-1.199)	(-0.156)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2021$	-0.073*	-0.020	0.017	-0.041	-0.012	-0.032**	0.041	0.005	0.007
	(-1.938)	(-1.429)	(1.148)	(-0.741)	(-0.662)	(-2.264)	(0.717)	(0.226)	(0.461)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2022$	0.003	-0.023**	0.017	0.015	-0.017	-0.037***	0.017	-0.040**	-0.004
	(0.062)	(-1.973)	(1.220)	(0.268)	(-0.897)	(-2.593)	(0.306)	(-2.003)	(-0.265)
$High\ \ln Vol_d^{\$\Delta} \times Year\ 2023$	0.042	-0.001	0.025	0.032	0.009	-0.030*	0.033	0.006	0.010
	(0.886)	(-0.078)	(1.583)	(0.549)	(0.424)	(-1.959)	(0.511)	(0.266)	(0.603)
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.	0.109	0.068	0.035	0.266	0.122	0.362	0.098	0.416	0.094
Obs.	1,427	1,427	1,427	1,427	1,427	1,427	1,427	1,427	1,427

Table IA.6: 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 (10) 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. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.

IA.1.5 Daily Realized Variance vs. 0DTE Trading Volume

	Using $Vol^{\$}$				Using $Vol^{\$\Delta}$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A. 0DTE Volume as Explanatory Variable								
$OI^{\$\Gamma}_{d-1}$	-0.256***	-0.219***	-0.014	-0.013	-0.265***	-0.229***	-0.016	-0.016
	(-3.927)	(-4.081)	(-1.011)	(-0.768)	(-4.000)	(-3.942)	(-1.056)	(-0.900)
$0DTE\ Volume_{d-1}$	0.272***	0.461***	0.027	0.055	0.270***	0.407***	0.028	0.062
	(7.472)	(5.205)	(1.338)	(0.903)	(7.396)	(4.667)	(1.389)	(1.061)
RV^{day}_{d-1}			0.493***	0.490***			0.492***	0.489***
			(3.312)	(3.276)			(3.307)	(3.272)
RV^{day}_{d-2}			0.486***	0.479***			0.486***	0.480***
			(3.075)	(3.053)			(3.078)	(3.054)
RV^{day}_{d-3}			0.075	0.078			0.075	0.078
			(0.749)	(0.775)			(0.749)	(0.778)
RV^{day}_{d-4}			-0.033	-0.037			-0.033	-0.037
			(-0.461)	(-0.522)			(-0.459)	(-0.517)
RV^{day}_{d-5}			-0.095	-0.097			-0.095	-0.098
			(-1.392)	(-1.420)			(-1.393)	(-1.421)
Year Dummies	No	Yes	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.077	0.136	0.725	0.724	0.075	0.136	0.725	0.724
Obs.	1,440	1,440	1,439	1,439	1,440	1,440	1,439	1,439
Panel B. 0DTE% as Explanatory Variable								
$OI^{\$\Gamma}_{d-1}$	-0.225***	-0.163***	-0.009	-0.001	-0.232***	-0.140***	-0.006	0.008
	(-3.609)	(-3.541)	(-0.743)	(-0.078)	(-3.855)	(-3.521)	(-0.497)	(0.620)
$0DTE\%_{d-1}$	0.194***	-0.018	0.009	-0.038	0.124***	-0.083	-0.002	-0.048**
	(6.443)	(-0.321)	(0.549)	(-1.495)	(5.466)	(-1.282)	(-0.127)	(-2.011)
RV^{day}_{d-1}			0.496***	0.495***			0.497***	0.493***
			(3.350)	(3.349)			(3.365)	(3.345)
RV^{day}_{d-2}			0.487***	0.479***			0.488***	0.479***
			(3.095)	(3.058)			(3.101)	(3.056)
RV^{day}_{d-3}			0.073	0.076			0.072	0.078
			(0.736)	(0.768)			(0.738)	(0.789)
RV^{day}_{d-4}			-0.031	-0.037			-0.030	-0.037
			(-0.428)	(-0.512)			(-0.413)	(-0.516)
RV^{day}_{d-5}			-0.095	-0.099			-0.095	-0.099
			(-1.394)	(-1.437)			(-1.390)	(-1.437)
Year Dummies	No	Yes	No	Yes	No	Yes	No	Yes
R-squared Adj.	0.053	0.123	0.725	0.724	0.036	0.124	0.725	0.725
Obs.	1,440	1,440	1,439	1,439	1,440	1,440	1,439	1,439

Table IA.7: 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 variables (except for dummies) are standardized to unit variance. t-statistics based on Newey and West (1987) standard errors with five lags are reported in parentheses. The sample period is from 01/2012 to 14/06/2023.