Intermediary Option Pricing*

Julian Terstegge
Copenhagen Business School

Latest Version
This Version: December 1, 2024

Abstract

I show that the risk premium in S&P 500 options is negative overnight, outside of regular exchange trading hours, but insignificant intraday, when the underlying equities are highly liquid. Intermediaries' inventory risk can explain this finding: Dealers have a net-short position in put options, which exposes them to overnight equity "gap risk", the risk that equity prices change overnight, since overnight equity liquidity is too low for continuous delta-hedging. In contrast, intraday equity liquidity presents few such obstacles. Dealers' resulting inventory risk predicts overnight option risk premia. Supporting this channel, the growth of overnight equity trading around 2006 reduces the magnitude of the option risk premium. I conclude that the risk premium in S&P 500 options results from the combination of options demand and overnight equity illiquidity, which expose risk-averse intermediaries to unhedgeable inventory risk.

Keywords: Asset Pricing, Intermediation, Derivatives, Inventory Risk, Liquidity

JEL Codes: G10, G12, G13, G14

*I am grateful for comments from Pierre Collin-Dufresne, Paul Fontanier, Stefano Giglio, Theis Ingerslev Jensen, Petri Jylhae (discussant), Ron Kaniel, Lars Christian Larsen, Anton Lines, Dmitriy Muravyev, Lasse Heje Pedersen, Markus Pelger, Tobias Siechert, Alessandro Spina, Johannes Stroebel, Stephen Szaura, Anders Bjerre Trolle, Paul Whelan, and seminar participants at the 2024 Macro Finance Society Workshop Poster Session, the 8th HEC Paris Finance PhD Workshop, and the 2024 Nordic Finance Network PhD Workshop. I gratefully acknowledge financial support from the Center for Financial Frictions, grant no. DNRF102, and the Center for Big Data in Finance, grant no. DNRF167.
Contact information: julianterstegge.com, jte.fi@cbs.dk

In the seminal model of Black and Scholes (1973) and Merton (1973), delta-hedged option returns equal the risk-free rate, since a continuously adjusted delta hedge eliminates options' exposure to equity market risk. However, empirical evidence shows that average delta-hedged option returns are significantly negative, especially for put options on equity indices.[1] As a result, a large literature seeks to rationalize delta-hedged option returns, commonly referred to as "option risk premia". These models can be separated into two classes: Representative-investor models, where option risk premia reflect representative-investors' consumption risk, and intermediary models, where dealers sell options to investors and negative option risk premia reflect compensation for the resulting inventory risk.[2]

This paper makes four contributions, using data on S&P 500 equity index options. (*i*) I show that put option risk premia are significantly negative overnight, where regular equity exchanges are closed and the Merton assumption of continuous delta-hedging is violated, but put option risk premia are not significantly different from the risk-free rate intraday, when U.S. equity markets are highly liquid and there are few obstacles to continuous delta-hedging. I find no risk-premia in call options over my sample period (2011 to 2023).[3] (*ii*) Addressing the difference between puts and calls, I show that dealers' short position in puts exposes them to the risk of overnight equity price changes (equity price "gaps"). In contrast, dealers' inventory of call options is balanced between long and short positions, resulting in relatively little exposure to gap risk. This finding suggests that equity liquidity impacts option risk premia through dealers' inventory risk. (*iii*) Dealers' inventory exposure to overnight equity price gaps predicts overnight option risk premia. Level and predictability of overnight option risk premia are significantly elevated in times of heightened equity return volatility. (*iv*) I show that increasing overnight equity liquidity reduces the option risk premium. Around 2006, several market changes — such as regulation "national market systems" and the acquisition of major "electronic communication networks" by the Nyse and the Nasdaq — increased overnight equity trade volumes from Monday to Friday, but left the weekend period largely untradable. I document a significant reduction in the magnitude of Monday-to-Friday option risk premium relative to Friday-to-Monday option risk premium around

[1] See Coval and Shumway (2001), Bakshi and Kapadia (2003), and many subsequent papers.

[2] Bates (2022) discusses this separation of option pricing models.

[3] Following the literature, I compare the returns of out-of-the-money puts to out-of-the-money calls to avoid overlapping estimates due to put-call parity, i.e., I study puts whose strike price is below the current price of the underlying and calls whose strike price is above the current price of the underlying.

that time.

Relating my empirical results to theory, I conclude that the risk premium in S&P 500 options results from the combination of options demand and overnight equity illiquidity, which expose risk-averse intermediaries to unhedgeable inventory risk. Consumption-risk models of option risk premia could account for my findings if consumption-risk, or investor risk aversion, were specific to overnight periods. I reject this explanation, since there are significant intraday risk premia in other asset classes (Aleti and Bollerslev, 2024). Thus, I conclude that representative-investor consumption risk alone does not account for option risk premia. Instead, such consumption risk leads to options demand, which is reflected in option risk premia through dealers' resulting unhedgeable inventory risk. My results are important for two reasons. For one, options are widely used in academia for inference on investor preferences and beliefs. My results imply that option risk premia reflect a combination of the investor pricing kernel and the intermediary pricing kernel. For another, options are widely used for hedging purposes, with hundreds of billions of dollars in outstanding contracts across markets. My results predict that increasingly liquid (overnight) markets lead to a reduction in option risk premia, thus reducing investor hedging costs and improving risk sharing. Next, I describe how I derive each of my results.

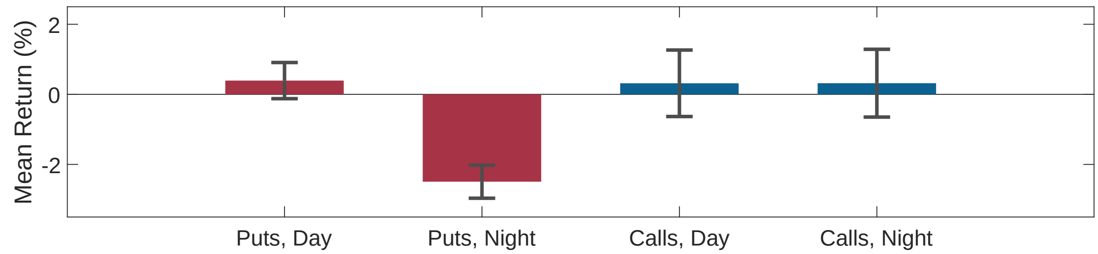
S&P 500 Options. This paper studies the market for options on the S&P 500 equity index. This market has three advantages: For one, S&P 500 options constitute the worlds most liquid exchange-traded options market, with an average monthly trade volume of $170bn as of 2022, enabling a return decomposition at high frequency, and highlighting the economic relevance of the market. In addition, S&P 500 options trade exclusively on the Chicago Board Options Exchange, which sells comprehensive option positions data. Finally, the underlying equities are highly liquidity intraday, during regular exchange trading hours, but relatively illiquid overnight, providing an instrument for dealers' inventory risk. Regular equity trading hours are 09:30 to 16:00 (E.T.), Monday to Friday, and the relatively illiquid pre-market hours cover only 04:00 to 09:30, while post-market hours cover 16:00 to 20:00. There is no equity trading on the major U.S. stock exchanges between 20:00 and 04:00. Equity futures trade almost 24 hours a day from Sunday 18:00 to Friday 17:00, but overnight volumes are reduced by an order of magnitude, especially between 20:00 and 04:00, when the major stock exchanges are closed. S&P 500 option trading hours are 09:30 to 16:15 and thus almost identical to equity trading hours.

S&P 500 option risk premia reside in puts, overnight. In the first part of the paper, I estimate option risk premia over day- and night periods. I measure option risk premia as delta-hedged option returns, which I subsequently refer to as option returns. This measurement of option risk premia is standard in the literature. Equity options are naturally exposed to equity market risk, but in the setting of Merton (1973) continuous delta-hedging via trades in equities reduces diffusive equity market risk to zero. Delta-hedged option returns reflect the remaining risk premia (Bates, 2022). I measure intraday option returns from 09:45 to 16:15 and overnight returns from 16:15 to 09:45. Measuring open prices after a 15 minute gap reduces potential bias from illiquid open quotes. Returns are delta-hedged at the start of the respective period and I show robustness of my findings to different methods for calculating delta.

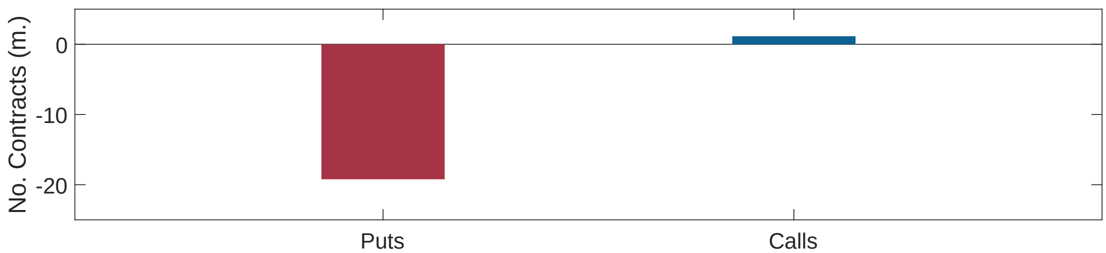
Panel (a) of Figure 1 summarizes the main finding of this section: S&P 500 put option returns are insignificant intraday, while being highly significantly negative overnight. Call option returns are insignificant over both day and night periods. My findings differ from Muravyev and Ni (2020), who estimate option risk premia over day- and night periods and estimate positive intraday option risk premia. In my sample, I find that positive intraday option risk premia result from options that do not trade at the open. Such options likely display positive intraday returns because overnight news is not fully reflected in their illiquid open quotes and, due to options' payoff profiles, news for options is asymmetrically positive. Excluding such illiquid opening quotes yields insignificant intraday risk premia. In addition, I find that overnight put option risk premia are concentrated in short-maturity, deep out-of-the-money puts, indicating that these options are particularly risky overnight. Intraday put option risk premia are insignificant across maturity or moneyness.

Dealers are exposed to overnight equity price gaps. To study the source of overnight put option risk premia, I estimate dealers' option inventory from a comprehensive dataset of S&P 500 option trades. I measure dealers' daily buy- and sell trade volume in S&P 500 options, and cumulate the daily net-buys (buys minus sells) into dealers' net-positions. Panel (b) of Figure 1 summarizes the main finding of this section. The dealer sector has a substantial net-short position in S&P 500 puts (on average about 19m contracts), while dealers' net-position in calls is comparatively small. Equivalent to the concentration of overnight put option risk premia, dealers' short put position is concentrated in short-maturity, deep out-of-the-money puts. I conclude that option risk premia occur where dealers are short (in puts) and liquidity is low (overnight).

Figure 1: Option Risk Premia Occur Where Dealers are Short and Liquidity is Low



(a) Option Returns



(b) Dealer Position

Note: This figure shows that option risk premia between 2011 and 2023 materialize overnight in put options, where dealers have a net-short position. Panel (a) shows 95% confidence intervals for return averages of out-of-the-money S&P 500 put- and call options. Returns are measured over "Day" periods between 09:45 and 16:15 and over "Night" periods between 16:15 and 09:45 (E.T.). Returns are delta-hedged at the beginning of the respective period. Panel (b) shows dealers' average net-position in S&P 500 options. The net-position is the cumulative sum of dealers' net-buys, where net-buys are the number of options bought minus the number of options sold. Returns are in percent and positions are in millions.

Going beyond the number of options in dealers' inventory, I estimate dealers' inventory exposure to gap risk as the return on dealers' option portfolio for different hypothetical returns of the underlying equities. I assume that dealers' option position is initially delta-hedged, but hedges are subsequently not adjusted. To that end, I simulate option returns from the Black-Scholes-Merton pricing model. I find that negative equity market returns lead to dealer inventory losses, while positive equity market returns have relatively little impact. This is because dealers are short out-of-the-money puts and delta-hedged returns on a short position in out-of-the-money puts are left skewed. I.e., losses from negative market returns are more pronounced than gains from positive market returns. Importantly, I explicitly estimate the risk of a large equity price move, rather than the standard approach of relying on marginal analysis based on option greeks, such as gamma.

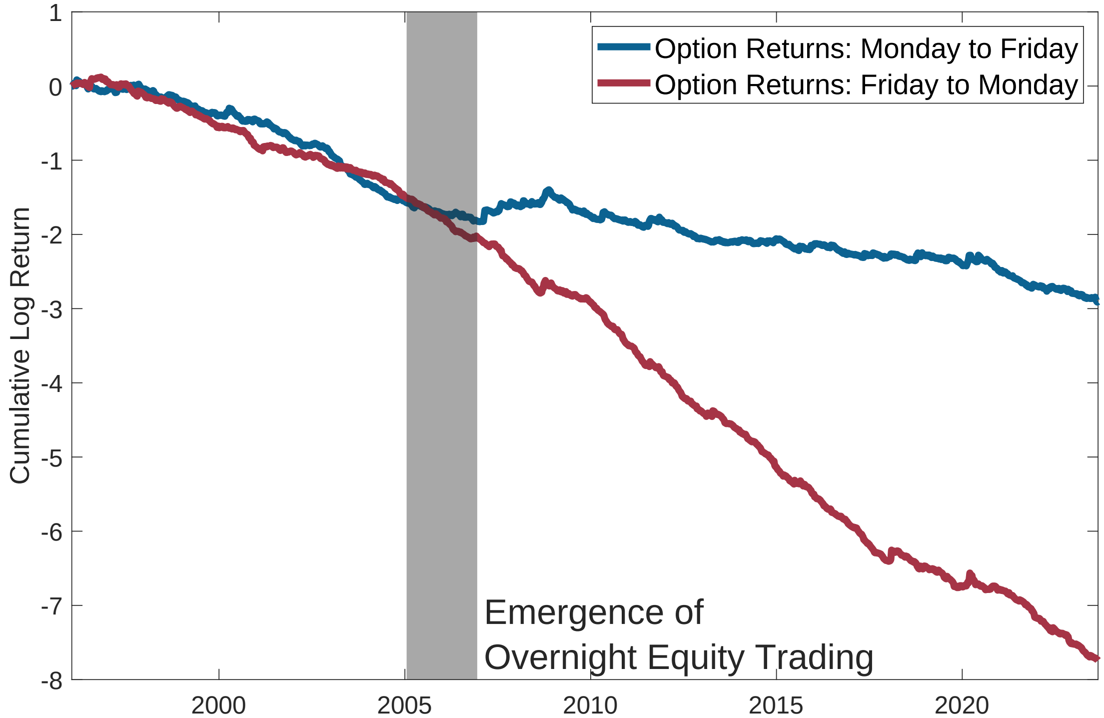
My novel measurement of dealers' inventory risk highlights the conceptual innovation in this paper, which addresses the high risk-premia in deep out-of-the-money puts. Following Garleanu, Pedersen, and Poteshman (2009), the extant literature on option dealer inventory risk has focused on dealers' net-gamma, which is the sum-product of dealers' net-position and options' gamma.[4] Net-gamma measures the local curvature of the value of dealers' option portfolio around the current price of the underlying, which approximates dealers' risk from jumps- and discrete trade time in the underlying, since jumps in the S&P 500 are small and sophisticated investors can trade at very high frequency, i.e., since jumps and discrete trade time will leave the underlying within a narrow range of its current value. Net-gamma cannot explain equity index put option risk premia, since put option risk premia are especially pronounced in out-of-the-money puts, while gamma is more pronounced in at-the-money puts. If gamma captured dealers' primary risk exposure, then at-the-money puts should appear most expensive, which is rejected in the data. In contrast, I provide evidence that dealers are exposed to the entire overnight return in the S&P 500, even if there are no jumps in the S&P 500, due to the daily market close of regular equity exchanges and the resulting overnight equity illiquidity. Overnight S&P 500 returns have reached -3.8% over my sample and I show that the returns of out-of-the-money puts are most affected by such large returns in the underlying. Thus, I explain why out-of-the-money puts are especially risky for dealers and consequently why risk premia in such options are especially pronounced.

Next, I demonstrate that overnight equity liquidity is too low for dealers to continuously adjust their delta-hedges. I estimate dealers' liquidity demand for the adjustment of delta-hedges, and find that in case of a -5% return in the S&P 500, dealers need to sell about \$8bn worth of equities in order to remain fully delta-hedged. For comparison, I show that the average overnight volume of the most liquid S&P 500 futures contract amounts to only about \$0.5bn an hour for most parts of the night. Futures contracts trade almost 24 hours a day on 5 days a week and are the most natural instruments for professional investors outside of regular exchange-trading hours. The average intraday volume of the most liquid S&P 500 futures contract amounts to \$20bn an hour, with an additional \$27bn hourly trade volume in the underlying S&P 500 constituent stocks themselves. I conclude that overnight equity market illiquidity presents a substantial obstacle for dealers' inventory delta-hedging, while intraday liquidity presents few obstacles.

Dealers' gap risk exposure predicts option risk premia. I regress option risk premia on lagged dealer gap risk exposure, and find that dealers' gap risk exposure predicts option risk premia overnight. A one standard deviation increase in dealers' risk exposure predicts a 57 basis

[4] Gamma is the second derivative of the option price with regards to the price of the underlying. That is, gamma measures the curvature of the option price function around the current price of the underlying.

Figure 2: Increasing Equity Trade Volume Lowers Option Risk Premia



Note: This figure shows cumulative returns of out-of-the-money, short-maturity S&P 500 put options. The top blue line cumulates returns from Monday to Friday, the bottom red-line cumulates returns from Friday to Monday. Returns are measured between trading days' market close at 16:15 (E.T.) and delta-hedged at the beginning of the respective period. Returns are in logs and are scaled to the same 10% annualized volatility. The vertical line indicates the emergence of overnight equity trading around 2006.01.

points decrease in overnight option returns. In a placebo test, I find that dealers' gap risk exposure predicts only a 4 basis points decrease in intraday option returns, which is not significant.

Testing another prediction of intermediary option pricing theory, I compare periods of high- and low equity market volatility. I find that, over high volatility periods, overnight put option risk premia are significantly elevated. In addition, I find significantly elevated predictive power of dealers' gap risk exposure for overnight option risk premia over such periods. Both results are consistent with the hypothesis that dealers require more compensation for their gap risk exposure over periods where large overnight equity price gaps are more likely.

Overnight equity trading reduces option risk premia. Finally, I exploit the increase of overnight equity trading around 2006 to study the impact of equity liquidity on option risk premia. Around 2006, several market changes, like the adoption of regulation "national market systems" (nms) and the acquisition of major "electronic communication networks" by the Nyse and the

Nasdaq, increased overnight equity trade volumes between Mondays and Fridays, but left the weekend period largely untradable.[5] This emergence of overnight equity trading yields a treatment group (Monday-to-Friday option risk premia) and a control group (Friday-to-Monday option risk premia). I document a significant reduction in the magnitude of Monday-to-Friday option risk premia relative to Friday-to-Monday option risk premia around that time. Figure 2 illustrates this result. Around 2006, a large and persistent gap emerges between the cumulative returns of S&P 500 put options Monday to Friday and Friday to Monday. I do not compare overnight returns to intraday returns around 2006, due to the lack of liquid high-frequency option prices around that time. These results relate to Dew-Becker and Giglio (2023), who show a decrease in option risk premia around the Great Financial Crisis. My findings suggest the increasing liquidity of overnight equity markets as an explanation.

Implications. My results suggest that S&P 500 option risk premia largely result from the combination of options demand and illiquidity in the underlying asset, which expose risk-averse intermediaries to unhedgeable inventory risk. This finding has three implications. (*i*) Option risk premia depend on dealers' inventory risk. Not all options should be expected to display insignificant intraday risk premia, since most underlying assets are not as liquid intraday as the S&P 500. This finding can potentially explain why extant estimates of the volatility risk premium vary between options on different underlying assets (Heston and Todorov, 2023). Similarly, I conclude that average intraday S&P 500 equity liquidity is sufficiently high, relative to dealers' option inventory, that average intraday option risk premia are insignificant. Significant intraday option risk premia might still arise in times of reduced liquidity or exceptional (jump) risk. E.g., Johannes, Kaeck, and Seeger (2023) find risk premia in S&P 500 options at high frequency around FOMC announcements. (*ii*) Security market design has a large impact on option risk premia and regulators who want to lower hedging costs for option market customers should consider the potentially beneficial impact of around-the-clock equity market liquidity. (*iii*) Investor demand for options translates into option risk premia through dealers' resulting unhedgeable inventory risk. As a result, option risk premia likely reflect a combination of the investor pricing kernel and the intermediary pricing kernel.

[5] In 2005, the Nasdaq held an initial public offering and purchased Instinet shortly thereafter. In 2006, the Nyse became a public company and shortly thereafter acquired Archipelago ECN, forming Nyse Arca.

I. Literature and Contribution

This paper contributes to several strands of the literature. First, this paper contributes to the literature on option risk premia. In the seminal model of Merton (1973), a continuously adjusted delta-hedge — achieved through trades in the underlying asset — reduces options' return variance to zero and thus reduces options' expected delta-hedged return to the risk free rate. However, Coval and Shumway (2001), Bakshi and Kapadia (2003), and many subsequent papers, find delta-hedged option returns to be significantly negative. I show that option risk premia are significantly negative outside of regular exchange trading hours, where the Black-Scholes assumption of continuous delta-hedging is violated, but delta-hedged returns are not significantly different from the risk-free rate intraday, when U.S. equity markets are highly liquid and there are few obstacles to continuous delta-hedging.

Second, this paper contributes to the literature on intermediaries in option markets. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) show demand pressure for options, which predicts option risk premia. Adding to this literature, I provide evidence that overnight equity illiquidity exposes option dealers to inventory risk, which can explain the negative risk premia in put options. Previous estimates of dealers' inventory risk do not explain the risk premia in deep out-of-the-money puts, since they focus on gamma, which is highest for at-the-money options. Dew-Becker and Giglio (2023) show a decline in option risk premia since about 2010, and suggest a decline in market frictions as a possible explanation. I explain the decline in option risk premia with the increasing liquidity of overnight markets.

A growing literature links option risk premia to the risk of rare "tail" events in the price of the underlying asset (e.g., Bollerslev and Todorov (2011), Andersen, Fusari, and Todorov (2015) and Andersen, Fusari, and Todorov (2017)). I find that the risk of large negative returns in the S&P 500 is reflected in the risk premia of S&P 500 options over periods where the S&P 500 is relatively illiquid, due to dealers' inventory risk. Significant intraday jump risk premia might still arise over periods where S&P 500 liquidity is unusually low, or jump risk is unusually high (e.g., around FOMC announcements (Johannes, Kaeck, and Seeger, 2023)).

The idea that some asset risk premia can be understood as compensation for intermediaries' inventory risk is well established (e.g. Stoll (1978), Amihud and Mendelson (1980) and Grossman and Miller (1988)). In such models, asset prices reflect dealers' inventory due to dealers' non-linear costs (Amihud and Mendelson, 1980) or due to dealers' risk aversion (O'hara and Oldfield, 1986). Dealers' effective risk aversion can arise for example from regulatory constraints, risk-management constraints, and funding constraints (Brunnermeier and Pedersen, 2009). Chen, Joslin, and Ni (2019) provide evidence that option dealer constraints are related to funding constraints. In this paper, I take dealers' effective risk-aversion as given, and instead focus on the question why dealers' option inventory exposes them to unhedgeable risk.

This paper contributes to the recent literature on liquidity premia in options markets. Cao and Han (2013) and Kanne, Korn, and Uhrig-Homburg (2023) show that stock option risk premia decrease in the liquidity of the underlying stocks. Christoffersen, Feunou, Jeon, and Ornthanalai (2021) estimate a model where the crash probability of the S&P 500 depends on its liquidity and find reduced option pricing errors. I contribute to this literature in four ways. (*a*) I study the difference between intraday and overnight option risk premia for the same options, thus alleviating concerns that illiquid stocks might differ in important ways from liquid stocks. (*b*) I show that the impact of underlying liquidity on option risk premia is conditional on dealer positions. (*c*) I show that option risk premia can turn insignificant over periods where the underlying asset is extremely liquid. (*d*) I exploit the emergence of overnight equity trading to point towards a causal link from equity liquidity to option risk premia.

Finally, this paper contributes to the recent literature on day-night patterns in options returns. Jones and Shemesh (2018) show that option risk premia are especially negative Friday to Monday relative to the rest of the week, which they attribute to a possible neglect of options' time decay by option traders. I explain low over-weekend option risk premia with the especially low equity trade volumes over such periods. Sheikh and Ronn (1994) find no significant difference between intraday and overnight option returns, likely due to their small sample. Muravyev and Ni (2020) find that intraday option returns are positive and attribute this finding to mispricing. In my sample, I find that this result stems from options that do not trade at market open. Excluding such illiquid quotes yields insignificant intraday option returns, which are consistent with an inventory-risk explanation. Orłowski, Schneider, and Trojani (2024) develop trading strategies for the study of skewness risk premia and find associated returns to be elevated overnight, which they attribute to uncertainty resolution by non-U.S investors. I show that risk premia in S&P 500 options are generally insignificant intraday, but significantly negative overnight. To the best of my knowledge, this is the first paper to link overnight option risk premia to intermediary hedging frictions.

There is a growing literature around day-night variation in equity returns. Hendershott, Livdan, and Rösch (2020) show that the capital asset pricing model performs poorly intraday, but works well overnight. They argue that a model with heterogeneous investors and time-varying constraints could rationalize this finding. Bogousslavsky (2021) argues that institutional constraints, such as elevated margin requirements and lending fees, incentivize arbitrageurs to reduce their equity positions before the end of the day. Boyarchenko, Larsen, and Whelan (2023) show that S&P 500 equity returns are unusually high around the open of European trading at 02:00 (E.T.), which they explain with dealers' inventory risk management.

II. Markets and Data

This section outlines the market characteristics of S&P 500 options, futures and equities. I briefly state data sources, while details on variable construction are in the respective sections.

S&P 500 Options. This paper studies S&P 500 equity index (SPX) options, i.e., put- and call options written on the S&P 500 equity index of U.S. large-cap stocks. SPX options are exchange-traded exclusively on the Chicago Board Options Exchange (CBOE) and were initially listed in 1983. While SPX option volumes were initially small, volumes have grown to about $200 billion a month in 2022 and open interest has grown to about $250 billion in 2022. Figure A.9 displays SPX options' volume and open interest over time. The SPX options market is the worlds' largest and most liquid equity options market. The high option liquidity enables a return decomposition at high frequency and the large market size makes SPX options an economically relevant market to study.

The original SPX options expired once a month on that months' 3^{rd} Friday. Recently, the CBOE has successively added SPXW options with different expiry dates.[6] To reduce computing time, I restrict the study of option returns to the standard SPX options, while for options positions I consider both SPX and SPXW options. Adding SPXW option returns does not change the findings of this paper. SPX options are liquid across a broad range of strike prices, which occur every $5. Liquidity is particularly high for out-of-the-money options, which are puts (calls) with strike prices below (above) the current value of the underlying index. SPX options are European

[6] Specifically, the CBOE added weekly Friday expiries in 2011.09, Wednesday expiries in 2016.02, Monday expiries in 2016.08, Tuesday expiries in 2022.04, and Thursday expiries in 2022.05.

options, so they can only be exercises at expiry. Table A.4 contains further contracts specifications and section A.2 contains further option market details.

S&P 500 Stocks: Day and Night. The S&P 500 equity index is a market-capitalization-weighted index of the equity value of 500 U.S.-listed firms across a broad range of industries. Figure A.2 displays cumulative returns of S&P 500 futures and shows that S&P 500 returns are of similar magnitude over days and nights over my sample. Figure A.4 displays the volatility of day and night S&P 500 futures returns and shows that day returns are about 30% more volatile throughout my sample. I conclude that fundamental equity risks are comparable between nights and days and, if anything, are elevated intraday. Thus, differences in fundamental risk cannot explain the day night variation in option returns that I document. Section A.3 describes the market for S&P 500 equities in greater detail.

Data Sources. From CBOE, I obtain SPX option prices and quotes at 15-minute intervals. Further, I obtain the daily "Open Close Volume" files that allow for the construction of dealer positions. From OptionMetrics, I obtain SPX option prices and quotes at the daily frequency. I obtain data on S&P 500 E-mini futures from Boyarchenko, Larsen, and Whelan (2023), who sample tick-level data of CME traded futures contracts. I obtain data on risk-free rates from the OptionMetrics IvyDB zero-curve file. Data on daily stock trading volume is from CRSP. High-frequency stock volumes are from Reuters. Details on variable construction are in the respective sections, and section A.1 provides a summary.

III. Option Risk Premia Reside in Puts, Overnight

This section shows that S&P 500 option risk premia are concentrated in put options, where they occur over night periods. Negative overnight put risk premia are concentrated in short-maturity, deep out-of-the money puts. Intraday put risk premia are insignificant across maturity and moneyness categories.

III.A. Delta-Hedged Returns as Risk Premia

I study delta-hedged option returns to prevent my analysis of option returns to be biased by equity risk premia. Figure A.10 displays the well-known option payoff profiles and illustrates that call (put) options tend to experience positive (negative) returns when the price of the underlying rises. Historically, U.S. equity returns have been positive, leading to positive (negative) returns of call (put) options. Delta-hedging controls for this effect and is standard-practice in options pricing research.[7]

I calculate delta-hedged option returns as

$$R_t^i = \frac{P_t^i - P_{t-1}^i \; - \; \Delta_{t-1}^i \; \times \; (SPX_t - SPX_{t-1})}{P_{t-1}^i} \tag{1}$$

where R_t^i is the return of option i over period t, P_t is the price of option i at the end of period t, SPX is the price of the S&P 500 index and Δ_{t-1}^i is the lagged delta of option i. Thus, the numerator consists of the dollar change in the option price minus the dollar change in the option price that can approximately be explained by changes in the price of the S&P 500. The denominator consists of the lagged option price only. Thus, the equation is based on the assumption that traders do not require any capital to trade the S&P 500 index. This is a common approach in option pricing research and a reasonable assumption due to the wide availability of liquid futures contracts during regular exchange trading hours (Muravyev and Ni, 2020).

An options' delta is the partial derivative of the option value function with regards to the price of the underlying asset ($\Delta = \frac{\partial P}{\partial S}$). If an (out of the money put) option has a delta of -0.2 and the S&P 500 rises by \$1 then the option price should fall by approximately \$0.2. Delta-hedging would involve an initial long position in 0.2 units of the index, such that a trader gains \$0.2 from the hedge-position that offset the $-$\$0.2 from the option position. The increasing value of the underlying SPX likely lead to a less negative option delta of now for example -0.15. To stay delta-hedged the trader will buy 0.05 units of the SPX, which can involve large dollar trades if the price of the underlying is high, since delta is in units of the underlying. For example, when the S&P 500 index value is at 5000, a small delta-adjustment of 0.05, involves a trade of \$250. This example highlights the aspect of delta and delta-hedging that is central to this paper. Delta-hedging is of first-order importance to reducing the risk of an options portfolio, but delta is a local linear approximation. Delta changes with the price of the underlying and a trader will have to keep trading the underlying to remain delta hedged. This paper shows that overnight equity volumes are too low for dealers to quickly adjust their delta-hedges, which exposes them to unhedgeable

[7] E.g., Bakshi and Kapadia (2003) and Jones and Shemesh (2018), among many others.

inventory risk.

III.B. Option Risk Premia: Day vs. Night

Delta-hedged returns of equity index options are highly negative, especially for deep out-of-the-money short-maturity put options (e.g., Bakshi, Charles, and Chen (1997), Coval and Shumway (2001) and Bakshi and Kapadia (2003)). In this section, I show that both these patterns are specific to night periods. S&P 500 put option returns are negative overnight, but not intraday and overnight put options returns are concentrated in short-maturity out-of-the-money puts, while intraday put returns do not vary by moneyness or time-to-maturity.

Data: Option Returns. I obtain high-frequency options data from the Chicago Board Options Exchange (CBOE) for the period of 2006 to 2023. The CBOE dataset aggregates data at the 15 minute frequency, such that the first available observation is at 09:45 (E.T.), 15 minutes after the regular options market open, and the last available observation is at 16:15, at the regular options market close. For each of these intervals the dataset provides options' bid quote, ask quote, and first-, last-, high- and low- trade price. Further, the dataset provides option volume, open interest and pre-calculated risk measures like delta and gamma. Andersen, Archakov, Grund, Hautsch, Li, Nasekin, Nolte, Pham, Taylor, and Todorov (2021) provide a detailed description of high-frequency option price data for U.S. markets.

To alleviate concerns of liquidity and data errors I apply several filters to the data. I exclude options with either a zero trade volume on any of the previous three days or a zero trade volume at the start of the respective return period. I.e., to be included in the night (day) portfolio an option needs to be traded for three consecutive days and be traded between 16:00 and 16:15 (09:30 and 09:45)) prior to the return period. I discard options with negative lagged bid-ask spreads or zero lagged bids or lagged mid quotes below \$0.05. I discard large hedged or unhedged reversal returns (returns above 1000% immediately followed by -90% or vice versa). Finally, I discard observations that violate no-arbitrage bounds.

My main sample period is 2011 to 2023. For one, options are comparatively more liquid over the later sample, yielding more reliable estimates of risk premia at high frequency. More importantly, the option positions data, that I describe in the next section, identify option market makers as a separate group only from 2011 onward. Before 2011, market makers trades have to be inferred as

Table I: Option Risk Premia: In Puts, Overnight

	Mean	t-stat	Std	Skew	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.49	-10.34	12.40	9.31	-12.66	-2.50	6.30
Day Return (%)	0.39	1.49	13.51	5.02	-10.38	-1.56	34.64
Night minus Day Return (%)	-2.88	-7.28	18.48	0.62	-19.15	-1.34	11.95
Panel (b): Calls							
Night Return (%)	0.32	0.64	27.72	10.13	-16.71	-2.41	18.44
Day Return (%)	0.32	0.65	22.75	4.89	-17.03	-3.06	56.58
Night minus Day Return (%)	0.00	0.01	36.38	2.86	-28.60	0.51	25.87

Note: This table shows that put option risk premia are significantly more negative over night periods than day periods, while there is no such difference for call option risk premia. Panel (a) shows summary statistics for S&P 500 put option returns, panel (b) contains calls, and both groups are restricted to out-of-the-money options. Within each panel, row 1 (2) contains returns between 16:15 and 09:45 (09:45 and 16:15). Returns are in percent and delta-hedged at the beginning of the respective period. The sample period is 2011 to 2023.

the residual to the other trader groups. In the appendix, I show that my main results are robust to including the early years 2006 to 2010.

I measure night returns from 16:15 to 09:45 (E.T.) and day returns from 09:45 to 16:15. I measure open prices at 09:45 since my dataset groups options data into 15 minute intervals, which has the added benefit of alleviating the concern of illiquid open quotes. Throughout the paper, I use mid-quotes to measure prices. I delta-hedge option returns with S&P 500 E-Mini futures at the start of the respective period, i.e., the delta-hedge for e.g., night returns is set up at 16:15 and subsequently not adjusted. I estimate options' delta from the Black-Scholes-Merton model, where I set the volatility of the underlying equal to the options' lagged implied volatility relative to the BSM model. I lag the implied volatility to avoid biases from the negative correlation between market volatility and market returns. In robustness checks I show that my results are robust to alternative delta calculations. Throughout the paper, I report option returns in excess of the risk-free rate, which does not impact my results, since risk-free rates over the period of a few hours are negligible.

Table I shows summary statistics for delta-hedged option returns. Panel (a) contains out-of-the-money put options, panel (b) contains out-of-the-money calls. Over my sample (2011.07 to 2023.08) S&P 500 put option experienced an average night return of -2.49%.[8] The associated

[8] Average returns are not annualized. Option risk premia are very large relative to most other traded assets.

Table II: Overnight Put Returns Reside Deep Out-of-the-Money at Short-Maturity

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-381.7 (−10.9)	-14.4 (−0.8)	-300.6 (−9.9)
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-85.4 (−5.0)	-22.7 (−4.7)	-69.3 (−6.2)
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	-56.8 (−5.0)	-20.1 (−4.1)	-45.1 (−4.6)
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	-68.4 (−4.0)	-58.9 (−1.6)	-62.7 (−4.0)
All		-292.1 (−11.0)	-19.6 (−1.6)	-228.4 (−10.1)

Note: The table shows average S&P 500 put option returns for eight portfolios, sorted by days to expiry and moneyness. Returns are measured from option market close at 16:15 to the subsequent market open at 09:45. Returns are in basis points and are delta-hedged at the beginning of the respective period. Newey-West t-statistics are in brackets. The sample period is 2011 to 2023.

Newey-West t-statistic exceeds 10. In contrast, put option intraday returns average only 0.39%. The difference between night and day returns is highly significant. Panel (b) shows that S&P 500 call options experienced an average night return of 0.32% and an equal average day return. Neither the night return, the day return or the difference between the two is significantly different from zero for call options.

The appendix contains several robustness tests. Table A.5 reports bootstrapped standard errors instead of Newey-West t-statistics. Table A.7 regresses the delta-hedged option returns on contemporaneous returns of the underlying equity index and reports summary stats for the resulting alphas. Table A.8 divides options' implied volatilities by 1.3 as inputs into the delta calculation to account for the volatility risk premium in implied volatilities. Table A.9 delta-hedges option returns via the pre-calculated deltas in the CBOE dataset.

Table II shows overnight S&P 500 put option returns by option portfolio. Options are sorted into a portfolio by moneyness and days to expiry at market close and held in that portfolio until the next market open. Put option risk premia are heavily concentrated in short-maturity, deep out-of-the-money options, where average night returns amount to −382 basis points. For comparison, longer maturity deep out-of-the-money put options have night returns of only about −14 basis points on average and short-maturity out-of-the-money puts have night returns of only about −85 basis points. The bottom right average return does not correspond to the top left average return in table above, since above I consider only out-of-the-money options. Table A.10 shows intraday S&P 500 put option returns by moneyness and time-to-expiry. Across portfolios, intraday put returns are close to zero. This result suggests that option returns vary along the dimensions of moneyness and time-to-expiry because of their different sensitivity to (overnight) market illiquidity, which I explore in subsequent sections. Tables A.11 and A.12 show intraday and overnight call option returns by moneyness and days-to-expiry. Corresponding to puts, intraday call risk premia are insignificant across portfolios. Overnight call risk premia are significant only for in-the-money options, due to their no-arbitrage relationship to out-of-the-money put options. Since European puts and calls with the same contract specifications have to be priced consistently, to avoid no-arbitrage violations, I compare out-of-the-money put options to out-of-the-money throughout the paper.

IV. Dealers' Position: Short Puts

This section shows that the dealer sector has a persistent short position in S&P 500 put options, while the position in call options fluctuates around zero. To that end, I document dealers' buy- and sell trades in S&P 500 options and cumulate these trades into positions. In call options, dealers' buy- and sell volumes are remarkably balanced, while in put options, dealers' sell volumes consistently exceed buy volumes, leading to short positions. Equivalent to overnight put option risk premia, dealers' short put position is concentrated in deep out-of-the-money, short-maturity puts. Dealers sell a particularly large volume of put options in times of low equity market volatility, highlighting the importance of equity market risk for dealer inventory risk.

IV.A. Option Trades: Dealers Sell Puts

A major advantage of the S&P 500 index options market for the study of intermediary asset pricing is the availability of comprehensive trade data. S&P 500 index options trade exclusively on the Chicago Board Options Exchange (CBOE) and the CBOE makes datasets commercially available that allow for the daily measurement of the options position of the dealer sector. Dealers'

Table III: Dealers Sell Puts

	Mean	Std	P10	P50	P90
Panel (a): Puts					
Buys (No. m.)	29.1	12.7	15.9	26.3	46.8
Sells (No. m.)	30.3	12.6	16.6	28.0	47.3
Net Buys (Buys - Sells)	-1.2	2.2	-3.8	-1.1	1.0
Panel (b): Calls					
Buys (No. m.)	17.5	7.3	9.8	15.8	27.8
Sells (No. m.)	17.4	7.3	9.6	15.7	27.8
Net Buys (Buys - Sells)	0.1	1.0	-1.1	0.1	1.3

Note: This table displays summary statistics for dealers' daily trade volume in S&P 500 options, separated by buy volume and sell volume. Trade volume is in millions of contracts. Panel (a) contains puts, panel (b) contains calls. The sample period is 2011 to 2023.

options position provide information on their risk exposures and risk management.

Data: Trade Volume by Trader Type. I obtain "Open-Close Volume files" from the CBOE. These files split daily option volumes by contract (puts vs calls, expiry date and strike price), by trader group ("market maker", "broker-dealer", "firm", "customer" and "professional customer"), and by volume type (volume bought vs volume sold). Throughout the paper, I refer to market makers as dealers. I focus on the sample periods of 2011 to 2023. Prior to 2011, market makers are not separately identified in the Open-Close Volume files, but have to be imputed as the counterparty to firms and customers. Focusing on the post 2011 period has the added benefit of increased option liquidity, which yields more reliable estimates of option risk premia at high frequency. S&P 500 options have a contract multiplier of 100, i.e., one option is written on 100 units of the underlying asset. To aid interpretability, I adjust units such that one option is linked to one unit of the underlying, i.e., I multiply all option volumes and positions by 100. I include all available S&P 500 options into the analysis: The standard monthly SPX options and the weekly SPXW options.

Table III shows dealers' daily trade volume in S&P 500 options. Dealers buy an average of 29.1 million puts a day, while they sell about 30.3 million puts a day. Thus, the dealer sector experiences net-buys of -1.2 million puts a day, where net-buys are calculated as $NetBuys_t^i = Buys_t^i - Sells_t^i$ of option i over day t. In contrast, the average dealer buy- and sell volume in call options is almost identical at 17.5 million contracts a day, leading to dealer net-buys in call options of approximately zero.

Who buys puts? The literature suggests that dealers negative net-buys in S&P 500 put options stem largely from sophisticated investors' hedging demands. Lemmon and Ni (2014) link equity index option trading to this motive, while they argue that trading in equity options (options on single stocks) is mostly driven by retail investors. Bollen and Whaley (2004) argue that institutional investors hold long positions in index put options as portfolio insurance. Chen, Joslin, and Ni (2019) interpret customers demand for put options as an indication for their aversion to economic crash risk. Goyenko and Zhang (2019) find end-user buying pressure in S&P 500 put options, but selling pressure in S&P 500 call options. In summary, various types of institutional investors demand equity index put options and there is no natural counterparty that could supply such options. As a result, intermediaries hold short put positions in their inventory.

IV.B. Option Positions: Dealers are Short Puts

I cumulate dealers' daily net-buys of S&P 500 options into dealer positions, via

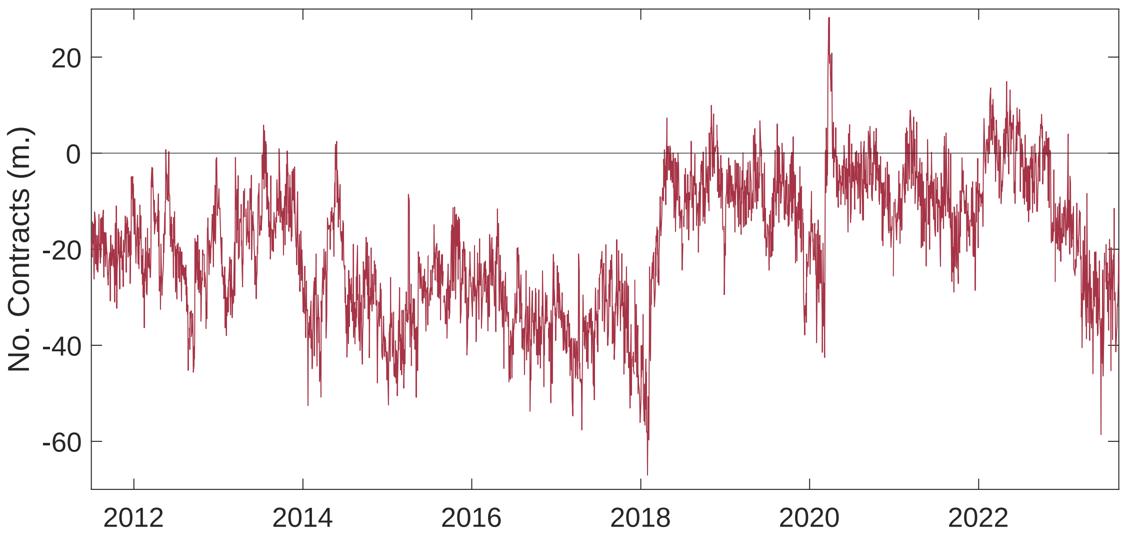
$$NetPosition_t^i = \sum_{k=1}^{t} NetBuys_k^i, \tag{2}$$

where k is a time index from the beginning of my sample to the end of the current day t. I.e., dealers' $NetPosition_t^i$ in option i at the end of day t is calculated as the cumulative sum over all past daily dealer $NetBuys_t^i$. Thus, $NetPosition_t^i$ is the number of contracts of option i that dealers are long minus the number of contracts of option i that dealers are short. Since options are regularly listed and subsequently expire, this cumulation yields dealers' option inventory after a burn-in period. I choose a burn-in period of six months and thus arrive at my sample period of 2011.07 to 2023.08. Figure A.13 contains a numerical example regarding the estimation of dealers' net-position.

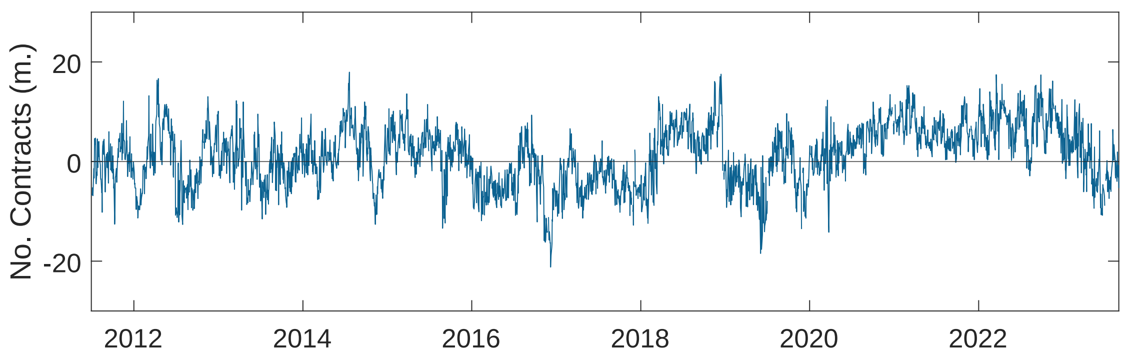
Figure 3 shows the time series of dealers' net-position in S&P 500 puts and calls. Dealers' position in call options oscillates between +10m contracts and −10m contracts, without any systematic pattern over most of the sample. Dealers' zero net-position in calls can rationalize the finding in the previous section that call returns are generally insignificant and do not vary between night periods, where liquidity is low, and day periods, where liquidity is high.

Dealers' position in puts is markedly different than their position in calls. In July 2011 dealers

Figure 3: Dealers' Net-Position: Short Puts



(a) Puts



(b) Calls

Note: This figure shows that dealers have a persistently negative net-position in S&P 500 put options. Panel (a) shows the daily time-series of dealers' net-position in S&P 500 puts, panel (b) contains calls. Dealers' net-position is the number of contracts that dealers are long minus the number of contracts that dealers are short. Section IV describes the variable construction. Net-positions are in million contracts.

have a short position in about 20 million puts. This short position gradually increases to around 50 million contracts in early 2018. Subsequently, dealers' net-position oscillates at around -10 million contracts. Dealers' short put position can rationalize the finding in the previous section that put returns are generally negative and are significantly more negative overnight, where hedging frictions are elevated. Dealers' put position is negative on the vast majority of days, but experiences a significant shift in early 2018. I address this shift in the "inventory risk management" paragraph below.

Those put options where I find the most negative night returns are also the put options where

Table IV: Dealers' Short Put Position Resides Deep Out-of-the-Money at Short-Maturity

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-13.54	-3.32	-16.86
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-0.47	-1.47	-1.94
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	0.38	-0.07	0.32
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	0.47	0.17	0.63
All		-13.15	-4.70	-17.85

Note: This table shows dealers' net position in S&P 500 put options by moneyness and days to expiry. Dealer net position is the number of contracts that dealers are long minus the number of contracts that dealers are short. Section IV describes the variable construction. Numbers are in millions. The sample period is 2011 to 2023.

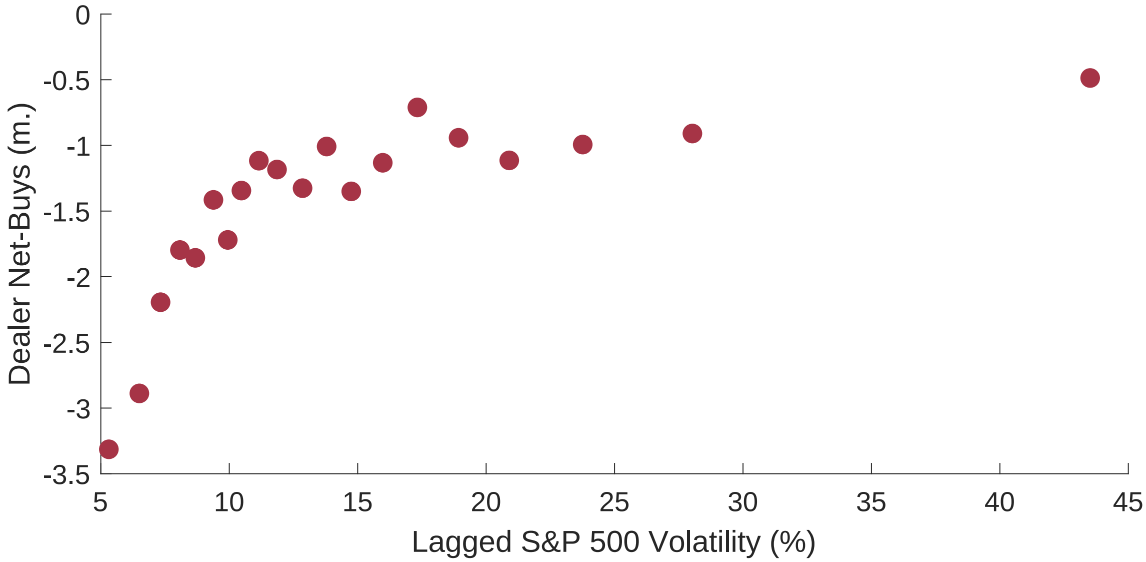
I find the most negative dealer positions. Table IV shows dealers' position in S&P 500 put options across option portfolios. Following the procedure for the option return tables in the previous section, I sort options into portfolios by moneyness and days to expiry at market close and report dealer positions across portfolios. Options' are re-assigned at the next market close. Dealers short position of on average about 20 million puts is concentrated in short-maturity, out-of-the-money options, where I find a short positions of about 14 million contracts. It is remarkable that the pattern in dealer positions across put portfolios corresponds to the pattern in overnight put option returns across portfolios in table II, while there is no such pattern in intraday put option returns in table A.10. This correspondence is consistent with an interpretation where option returns compensate dealers for inventory risk from overnight market illiquidity.

IV.C. Dealers' Inventory Risk Management: Equity Market Risk

Dealers sell more put options during times when equity market volatility is relatively low, suggesting that (*i*) dealers actively manage their options inventory and (*ii*) that equity market risk is a meaningful part of dealers inventory risk. The first example of this is the change in dealers' short put position around 2018 that is visible in figure 3. Figure A.5 shows the time series of S&P 500 index volatility, measured as the annualized volatility of daily close-to-close returns of the S&P 500 index over a rolling 365 day window. Realized S&P 500 volatility is unusually low leading into 2018 and is persistently higher afterwards.[9] Thus, dealers' carry a smaller short put position in their inventory after 2018, but each option exposes them to more risk, due to the

[9]February 5^{th} 2018 marks the event that traders refer to as "Volmageddon". Augustin, Cheng, and Van den Bergen (2021) describe the event.

Figure 4: Dealers' Sell More Puts when Equity Returns are Less Volatile



Note: This figure plots dealers' average net-buys for different groups of lagged S&P 500 index return volatility. Net-Buys are the daily number of S&P 500 put options bought minus the number of S&P 500 put options sold. Volatility is measured for a rolling window of 10 daily close-to-close returns and is lagged by one day.

higher return volatility of the underlying. Gruenthaler (2022) finds that option dealers manage their net-vega exposure in anticipation of spikes in implied volatility. In contrast, I find that equity market risk is the central component of dealers' inventory risk. The importance of equity market risk for dealers' inventory risk is consistent with the interpretation that option risk premia materialize overnight because obstacles to delta-hedging expose dealers to equity market risk.

Dealers' inventory risk management in the face of equity market risk is clearly visible in dealers' trade volumes. Figure 4 shows a binscatter plot for dealers' daily net-buys for 20 bins of lagged realized volatility of the underlying S&P 500 index. Dealers sell more puts when equity market risk is relatively low. For example, when lagged S&P 500 return volatility is around 5, then dealers sell an average of 3.4 million put options a day. In contrast, when lagged S&P 500 return volatility is around 17, then dealers sell an average of only 1 million put options a day. The relationship between equity market risk and dealer net-buys is almost monotonous, though the figure suggests a relationship that is logarithmic rather than linear. Of course, this figure does not show whether trades in puts are driven from dealers and customers. It is possible that customers demand more put options when equity markets are calm. However, this seems less intuitive from a risk perspective than the other side of the argument, that dealers are more willing to sell puts when equity markets are calm.

V. Dealers' Exposure to Overnight Equity Price Gaps

This section shows that option risk premia are increasing in dealers' inventory exposure to gap risk, and this relationship is restricted to night periods. To that end, I estimate dealers' inventory exposure to overnight equity price gaps and regress day- and night option risk premia onto dealers' gap risk exposure. I find that dealers are substantially exposed to negative overnight equity price gaps due to the combination of short put positions and low overnight equity liquidity. The resulting inventory risk predicts option risk premia overnight, but not intraday. Dealers' equity gap risk exposure spikes into the 3^{rd} Friday option expiry, rationalizing why option risk premia are concentrated around that period.

V.A. Estimating Dealers' Exposure to Gap Risk

I exploit dealers' option positions to estimate their exposure to different market scenarios. Specifically, I estimate the *Profit and Loss (PnL)* of dealers' option positions, as

$$\widehat{PnL}_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times \left[\widehat{P}_{t+1}^i - P_t^i - \Delta_t^i \times (\widehat{SPX}_{t+1} - SPX_t)\right] \tag{3}$$

where $\widehat{PnL}_{t+1}$ is the estimated PnL over period $t+1$, $NetPosition_t^i$ is dealers' net-position in option i at the end of day t as described in section IV, $\widehat{P}_{t+1}^i$ is the estimated market price of option i, Δ_t^i is the delta of option i, and $\widehat{SPX}_{t+1}$ is the estimated value of the S&P 500. Thus, I estimate the PnL that the dealer sector will incur under different scenarios for P and SPX. This estimation approach is very flexible as it can accommodate any dynamics for P and SPX. However, the estimation requires some assumptions. Estimating future option prices as a function of the price of the underlying requires an option pricing model. In the spirit of simplicity, I choose the Black-Scholes-Merton model. The choice of pricing model is immaterial for the results in this paper, as long as the value of the option is a convex function of the value of the underlying, such that changes in the price of the underlying change the options' delta. To estimate the PnL, I assume that dealers are initially fully delta-hedged, but subsequently do not adjust their option positions or hedges. This is a reasonable approximation over nights where market liquidity is low.

Further, I assume that dealers have the same dollar position in every options contract, yielding an equal-weighted PnL estimate. Via this assumption I abstract from dealers' margin requirements (e.g., section A.2 and Hitzemann, Hofmann, Uhrig-Homburg, and Wagner (2021)).

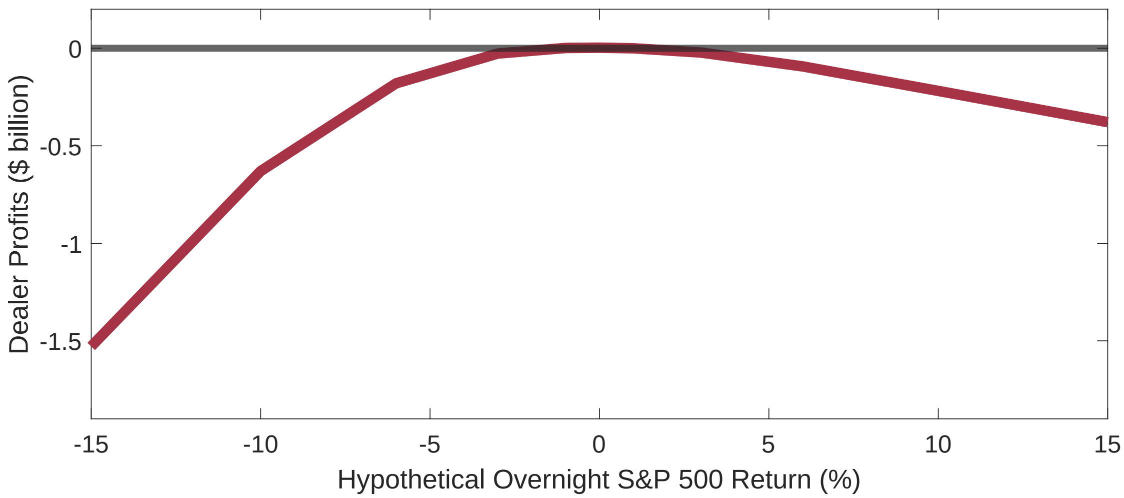
I estimate dealers' exposure to equity market risk and stochastic volatility risk. To estimate $\widehat{PnL}_{t+1}$ in equation 3 from e.g., a -10% return in the underlying S&P 500 index, I estimate $\widehat{P}^i_{t+1}$ as the Black-Scholes-Merton price of option i at the end of period $t+1$, assuming that $\sigma^i_{t+1} = \sigma^i_t$ and $\widehat{SPX}_{t+1} = SPX_t \times 0.9$, where σ describes options' implied volatility relative to the Black-Scholes-Merton model. To estimate $\widehat{PnL}_{t+1}$ in equation 3 from e.g., a 200% increase in options' implied volatilities, I estimate $\widehat{P}^i_{t+1}$ as the Black-Scholes-Merton price of option i at the end of period $t+1$, assuming that $\sigma^i_{t+1} = \sigma^i_t \times 2$ and $\widehat{SPX}_{t+1} = SPX_t$. I.e., I change one market variable, while holding the other constant. In practice, equity market returns and volatilities are negatively correlated.

V.B. Dealers' Exposure to Gap Risk

Figure 5 illustrates dealers' exposure to equity price gap risk. The figure shows the estimated profits from dealers' option portfolio for different hypothetical returns of the underlying S&P 500, assuming initial delta-hedges that are subsequently not adjusted. The figure shows that for example a -10% return in the S&P 500 index would lead to a loss of about \$700m. Section IV shows that dealers have an average net short position in about 20 million options. That is, in case of a -10% index return, dealers loose about \$35 for every \$1 option position. Losses can exceed 100% for two reasons. For one, I assume positions in the underlying asset for the purposes of delta-hedging, which add to the numerator in the return calculation but do not add to the denominator, since futures can be traded with very few margin requirements. More importantly, the losses accrue from price increases on short positions. The estimated PnL for a 0% return in the S&P 500 is comparably small at \$2.5m and stems from the time-decay of the option value.

Figure A.16 shows that a 200% increase in options' implied volatilities would lead to a loss of about \$400m. Options' prices increase with their implied volatilities and whoever holds short options positions incurs losses. Such spikes in expected volatility tend to occur in times of economic crises, like the Great Financial Crisis of 2008 or the Covid Crash of 2020, but typically revert quickly to normal levels. Dealers' exposure to stochastic volatility risk is unlikely to explain

Figure 5: Dealers are Exposed to Overnight Equity Gap Risk



Note: This figure shows that dealers are exposed to overnight equity price Gap Risk, the risk that equity prices change between market close and open. The figure shows estimated dealer PnL for different hypothetical overnight returns of the underlying S&P 500 index. Dealers' option positions are equal weighted, assuming a $1 position in every option. Option returns are delta-hedged, but hedges are subsequently not adjusted. Section V describes the variable construction. The sample period is 2011 to 2023.

put option risk premia, since I show that risk premia are insignificant intraday. Extremely high intraday equity trade volumes can rationalize why dealers face little equity market risk intraday, while it is highly unlikely that, in case of an implied volatility spike, dealers can quickly buy back their options from customers intraday, such that they avoid those losses.

Dealers might not require large compensation for stochastic volatility risk, since volatility spikes are highly mean reverting. Dealers might experience a negative PnL from increases in options' implied volatilities, but can expect those losses to reverse over the following days or weeks as long as they avoid a forced liquidation of their portfolio. An alternative potential explanation for the absence of stochastic volatility risk premia in (intraday) option returns is that dealers' hold offsetting positions in other equity options or structured products that insulate them from such shocks. Both interpretation are consistent with Dew-Becker, Giglio, Le, and Rodriguez (2017), who find that changes in expected volatility can be hedged costlessly.

Dealers' equity price gap risk is concentrated in deep out-of-the-money short-maturity put options. I estimate dealers' gap risk exposure as

$$Dealers'\ Gap\ Risk_t = \widehat{PnL}_{t+1} \mid SPX_{t+1} = SPX_t \times 0.94 \tag{4}$$

Table V: Dealers' Gap Risk from Puts Resides Deep Out-of-the-Money at Short-Maturity

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \|\Delta\| \leq 0.25$	Deep Out of the Money	-178.9	-1.2	-180.2
$0.25 < \|\Delta\| \leq 0.50$	Out of the Money	0.6	-0.1	0.5
$0.50 < \|\Delta\| \leq 0.75$	In the Money	0.8	-0.0	0.8
$0.75 < \|\Delta\| \leq 1.00$	Deep In the Money	0.1	-0.0	0.1
All		-177.4	-1.4	-178.8

Note: The table shows the estimated dealer Profit-and-Loss from a -6% return in the underlying S&P 500 index by portfolio of put options. Section V describes the variable construction. Numbers are in million dollars. The sample period is 2011 - 2023.

, i.e., as the estimated profits on dealers' option portfolio given a 6% decline in the value of the underlying. Table V separates dealers' gap risk exposure into put option portfolios. I estimate that a -6% S&P 500 return leads to dealer losses from put options of $-\$178.8$m. $-\$178.9$m of the losses can be attributed to short-maturity, deep out-of-the-money puts. Table A.14 shows the corresponding numbers for call options, and does not reveal any large risk exposures. The concentration of risk has two causes: One, dealers short positions are heavily concentrated in these options and two, short-maturity out-of-the-money options' returns are most sensitive to underlying returns (see figure A.11).

My approach to estimating dealers' exposure to equity market risk is new to the literature. Since the work of Garleanu, Pedersen, and Poteshman (2009), the literature has focused on dealers' net-gamma and net-vega as measures of jump- and volatility-risk respectively. Net-gamma is the sum-product of dealers' net positions across options contracts and those options' gamma. Gamma is a "Greek" option risk-measure that approximates the change in delta from changes in the price of the underlying. Thus, dealers' net-gamma approximates the degree to which dealers' need to adjust their delta-hedges due to *small* underlying price changes. In contrast, my estimation can accommodate underlying price changes of any size and yield estimated portfolio losses as well as estimated delta changes.

V.C. Dealers' Gap Risk and Expected Option Returns

I explore the effects of dealers' equity market risk exposure on option returns by estimating

Table VI: Option Returns on Dealers' Gap Risk: Significant Overnight

	(1)	(2)	(3)	(4) Puts	(5) Calls
Dealers' Gap Risk	-32.3***	-32.2***	-4.0	-3.5	-35.5
	(-4.80)	(-4.79)	(-0.47)	(-0.31)	(-1.44)
Night		-85.0***	-84.6***	-153.3***	-12.1
		(-3.28)	(-3.27)	(-7.71)	(-0.29)
Dealers' Gap Risk x Night			-56.5***	-67.0***	-7.4
			(-4.19)	(-3.73)	(-0.19)
Constant	-23.2*	18.6	18.5	17.3	19.7
	(-1.79)	(0.98)	(0.97)	(1.11)	(0.74)
Observations	43,256	43,256	43,256	22,084	21,172
R2-adjusted	0.00	0.00	0.00	0.01	0.00

Note: This table shows that dealers' equity market gap risk predicts option risk premia, but only over night periods. The table presents regression estimates of Equation 5. I regress portfolio-level option returns on the portfolio-level measure of dealer gap risk presented in Section V and a dummy for night-periods. Option returns are overnight and intraday for the four out-of-the-money put- and call option portfolios from tables II and A.12. Returns are in basis points and are delta-hedged at the beginning of the respective period. Column (4) contains only the four put portfolios, column (5) contains only the four call portfolios. Gap risk is standardized to zero mean and unit variance. Standard errors are clustered within each day. The sample period is 2011 to 2023.

the following regression specification:

$$R_t^i = \beta_1 GapRisk_{t-1}^i + \beta_2 \times Night_t + \beta_3 GapRisk_{t-1}^i \times Night_t + \epsilon_t^i \quad (5)$$

where $R_{i,t}$ is the return of option portfolio i over period t, and $GapRisk_{t-1}^i$ contains the negative of the estimated dealer PnL from a -6% S&P 500 return in portfolio i at the end of period $t-1$. I measure *GapRisk* as the *negative* of the estimated dealer PnL from a -6% S&P 500 index return, such that higher values indicate more risk. Option returns are overnight and intraday for the four out-of-the-money put- and call option portfolios from tables II and A.12. I.e., returns and risks are measured at the option portfolio level with portfolio, in order to obtain a continuous panel of return observations across moneyness and time-to-expiry, despite the strict liquidity subsets. Standard errors are clustered at the day level. Returns are in basis points, dealer gap risk is standardized to zero mean and unit variance.

Table VI provides regression estimates of Equation 5. Column (1) shows that dealers' gap risk across option portfolios has significant predictive power for option risk premia. A one standard deviation increase in dealers' gap risk exposure predicts a decrease in option returns of 32 basis points. Table A.15 shows summary statistics for dealers' aggregate gap risk exposure. A one stan-

Table VII: Overnight Put Option Risk Premia Increase in Volatile Periods

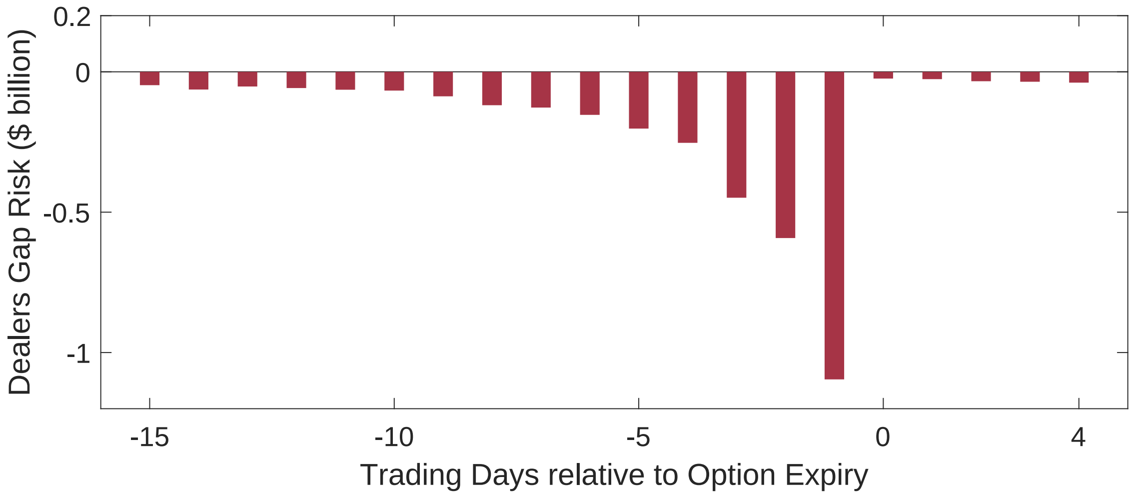
	(1)	(2)	(3) Puts	(4) Calls
Dealers' Gap Risk	-61.5***	-39.5***	-46.2***	-36.1
	(-5.82)	(-3.23)	(-2.81)	(-1.01)
Volatility	-58.4*	-58.4*	-106.2***	-15.9
	(-1.67)	(-1.67)	(-4.43)	(-0.27)
Dealers' Gap Risk x Volatility		-61.5**	-74.2**	-19.2
		(-2.48)	(-2.34)	(-0.34)
Constant	-36.8	-37.8	-84.3***	14.8
	(-1.58)	(-1.63)	(-5.08)	(0.40)
Observations	21,249	21,249	10,945	10,304
R2-adjusted	0.00	0.00	0.01	0.00

Note: This table regresses overnight option risk premia on lagged dealer gap risk exposure and a dummy for periods of high equity volatility. The volatility dummy indicates periods where the lagged 10-day return volatility of the S&P 500 is above its sample median. Option returns are overnight and intraday for the four out-of-the-money put- and call option portfolios from tables II and A.12. Dealers' gap risk exposure is at the option portfolio level as described in section V. Returns are in basis points and are delta-hedged at the beginning of the respective period. Gap risk is standardized to zero mean and unit variance. Column (3) contains only the four put portfolios, column (4) contains only the four call portfolios. The sample period is 2011 to 2023.

dard deviation increase in dealers' gap risk exposure corresponds to $430m increase in projected losses. Column (2) adds a dummy for night periods and confirms the finding that option returns are significantly more negative overnight, by 85 basis points. Column (3) interacts dealers' gap risk with the night dummy and shows that the predictive power of dealer risk for option returns is specific to night periods. A one standard deviation increase in dealers' gap risk predicts a decrease of 4 basis points for intraday returns, but a decrease of 57 basis points for night returns. Standard errors are clustered at the daily level, since my measure of dealers' gap risk does not vary between day- and night periods. In unreported results, I find that double-clustering standard errors by day and $Portfolio \times Month$ does not affect the significance of the results. Column (4) sub-sets the sample to put option portfolios, leading to more negative night returns and overnight predictability that is approximately unchanged. Column (5) sub-sets the sample to call option portfolios. Consistent with the previous results of insignificant call option risk premia and insignificant dealer inventories of calls, the estimation reveals no overnight risk premia and no predictability via dealer inventories.

Testing another prediction of intermediary option pricing theory, I compare periods of high- and low equity market volatility. Table VII regresses overnight option risk premia on lagged

Figure 6: Dealers' Gap Risk: Spiking into 3^{rd} Friday Option Expiry



Note: This figure shows that dealers' gap risk spikes into the 3^{rd} Friday option expiry. The figure plots dealers' equity market gap risk as estimated in section V relative to each months' 3^{rd} Friday, where the standard SPX options regularly expire. Day 0 marks the 3^{rd} Friday, where risk is low since I consider positions at market close, when SPX options have already expired. The sample period is 2011 to 2023.

dealer gap risk exposure and a dummy for periods of high equity volatility. The volatility dummy indicates periods where the lagged 10-day return volatility of the S&P 500 is above its sample median. Option returns are overnight and intraday for the four out-of-the-money put- and call option portfolios. Dealers' gap risk exposure is at the option portfolio level as described above. Gap risk is standardized to zero mean and unit variance.

Column (1) shows that dealers' gap risk has significant predictive power for overnight option risk premia, but option risk premia are not generally elevated in periods of high equity return volatility. However, Column (2) shows that dealers' gap risk has significantly more predictive power for overnight option risk premia in periods of high equity return volatility. Column (3) subsets the regression sample to the four out-of-the-money put portfolios and shows both elevated risk premia and elevated return predictability in high volatility periods. Column (4) constitutes a placebo-test. I subset to the four out-of-the-money call option portfolios and I find neither elevated risk premia nor elevated predictability, consistent with the hypothesis that dealers' gap risk originates from put options.

V.D. Risk and Returns Spike Into the 3^{rd} Friday Option Expiry

Dealers' equity price gap risk and options' average night returns both become particularly pronounced over the days before the monthly expiry of the standard SPX options on 3^{rd} Friday. Figure 6 shows dealers' equity market gap risk relative to each months' 3^{rd} Friday, where the standard SPX options expire. Dealers' risk exposure increases almost monotonically until the day before option expiry. Day 0 marks the 3^{rd} Friday option expiry, where risk is low since I consider positions at market close, when SPX options have already expired. The spike in gap risk stems from the increased riskiness of short-maturity options that I outline above. Figure A.12 shows put returns around 3^{rd} Fridays and displays the same pattern for returns: Overnight put returns are especially pronounced immediately over the days leading up to the monthly 3^{rd} Friday option expiry date. Thus, the examination of 3^{rd} Fridays yields another dimension where dealers' risk exposure and option risk premia line up.

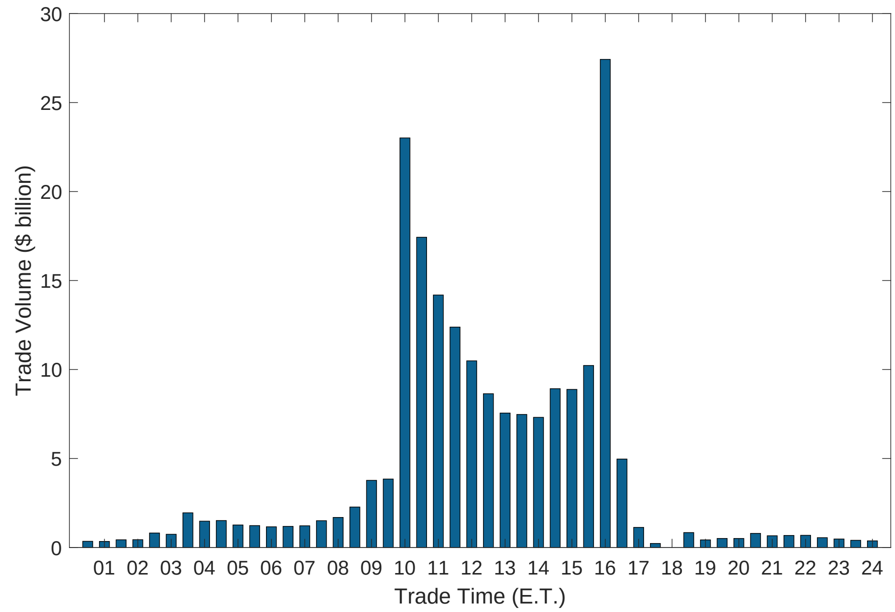
VI. Dealers' Liquidity Demand Exceeds Overnight Equity Volumes

This section shows that overnight equity trade volume is low relative to dealers' liquidity demand for delta-hedge adjustments. I describe the evolution of overnight equity trading in the US, and show 24h volume profiles for selected stocks and futures. I estimate that dealers' liquidity demand amounts to around \$8bn in case of a -5% return in the S&P 500, while the average overnight volume of S&P 500 futures contracts amounts to only about \$0.5bn an hour for most parts of the night.

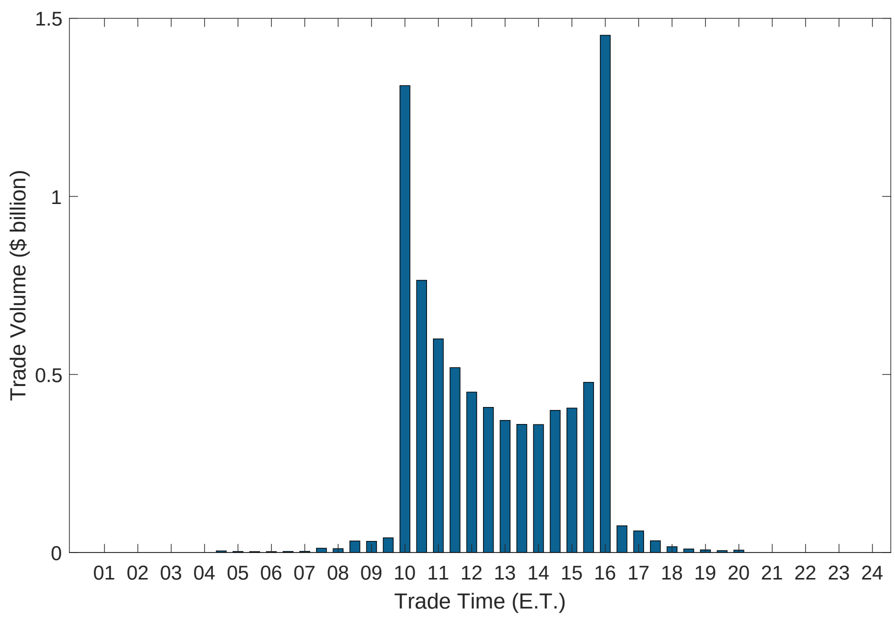
VI.A. Overnight Equity Trading

There are three dominant approaches to trade equities and adjust delta-hedges: Equities, equity ETFs and equity futures. Regarding equities, the current regular trading hours for all major U.S. exchanges are 09:30 to 16:00 (E.T.). These trading hours have been in place since 1985, when the NYSE moved the open time from 10:00. ETFs trade on the same exchanges as the underlying stocks and the trading hours are equivalent. Before the 1990s trading stocks outside of regular exchange trading hours would have required an over-the-counter transaction with a market maker over the telephone. In 1991 the Instinet trading system allowed institutional investors to trade stocks between 06:30 and 09:20. In 1998 the Nasdaq stock exchange introduced pre-market stock trading from 08:00 to 09:30, following a regulatory decision by the SEC. In the early 2000s, the

Figure 7: Equity Trade Volume is Small for Most Parts of the Night



(a) Futures



(b) Apple Inc.

Note: This figure shows average trade volumes for each 30-minute interval of the day. Panel (a) contains the most liquid S&P 500 E-mini futures contract, panel (b) contains Apple Inc. stocks. The sample period is 2011 to 2023.

NYSE, CME, and others introduced pre-market sessions of their own.

In 1998, regulation ATS (Alternative Trading Systems) distinguished ATS from registered exchanges, and increased reporting requirements, thus prompting ECNs (Electronic Communications Networks) to merge and register as exchanges. In 2001, Archipelago Electronic Communications Network and the Pacific Exchange merged to create ArcaEx, the first totally electronic stock exchange. In 2005, NYSE Hybrid Market was launched, creating a blend of floor-based auction and electronic trading. In 2006, New York Stock Exchange became a public company and shortly thereafter acquired Archipelago ECN. In connection with this, the NYSE eliminated the open outcry system on the floor. In 2005, in order to regain the competitive advantage lost to the rise of ECNs, Nasdaq held an initial public offering and purchased Instinet shortly thereafter. In 2005.04 Nasdaq trading hours were extended from 08:00 to 18:30 to 04:00 to 18:30. In 2006.09 Nasdaq extended trading hours further to 04:00 to 20:00, thus establishing the extended stock trading hours that are valid throughout my sample.

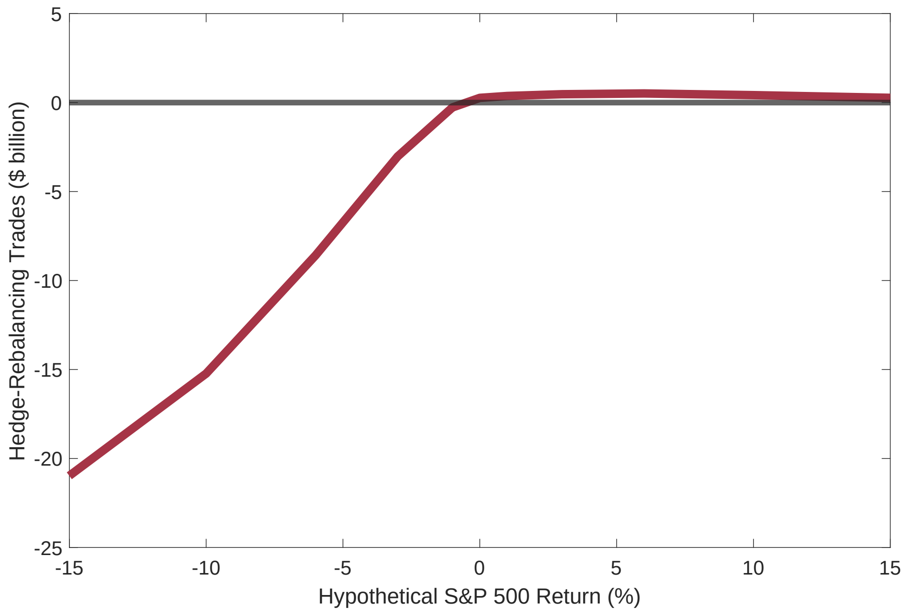
To illustrate stock trading hours, figure 7 panel (b) shows the average trade volume of Apple Inc. stocks for every 30-minute window of the trade day over my sample period of 2011 to 2023. The most obvious take-away is that there is no equity trading between 20:00 and 04:00 the subsequent morning. Trade volumes are barely perceptible from 04:00 to 07:30, and slightly elevated from 07:30 to 09:30. Trave volumes increase by orders of magnitude when stock markets open for regular trading at 09:30, with trade volumes following a U-shape from open to close. After-hours trading tends to be more liquid than pre-market trading, but volumes are still relatively small. There is no trading over the weekend, as stock trading ends on Friday's at 20:00 and resumes on Monday's at 04:00.

Figure A.7 displays the daily trade volume of the S&P 500 constituents stocks. Daily trade volumes were relatively low during the late 90s at around $20bn a day. Volumes increased around 2007 to more than $100bn a day, and have reached about $200bn a day after the 2020 Covid crisis. According to industry reports, as of Q1 2021 about 0.27% of the trade volume in S&P 500 stocks occurs during pre-market hours and about 0.12% occurs during post market hours.

Regarding S&P 500 futures trading hours, in 1995 S&P 500 futures began trading on the CME Globex electronic exchange. Trading hours followed the major U.S. equity trading hours: 09:30 to 16:00. In 1997, S&P 500 E-Mini futures began trading on the CME Globex platform, with trading hours from Sundays at 18:00 to Fridays at 17:00 and a daily maintenance period from 17:00 to 18:00.

S&P 500 futures volumes are low for most parts of the night, relative to dealers' liquidity

Figure 8: Dealers' Liquidity Demand



Note: This figure shows dealers' liquidity demand for the adjustment of delta-hedges in case of an equity market crash. Dealers' liquidity demand is estimated for different hypothetical returns of the underlying S&P 500 index via equation 6. The sample period is 2011 to 2023.

demand. Figure 7 panel (a) shows the dollar trading volume in S&P 500 E-Mini futures for each 30 minute interval of the day. Futures trade volumes are from Boyarchenko, Larsen, and Whelan (2023), who sample the most liquid futures contract every day. Volumes over regular trading hours are high, between $8bn and $15bn every 30 minutes. In contrast, overnight futures volumes are low, especially between 20:00 and 04:00, when the underlying equities do no trade, and futures trade volumes average about $250m every 30 minutes. I conclude that overnight trading volumes for U.S. equities are small relative to the delta-hedging needs of option dealers in case of a large market crash. As a result, option dealers are exposed to overnight equity market risk. The results in previous sections suggest that option risk premia compensate dealers for this risk exposure.

VI.B. Dealers' Liquidity Demand

How much would dealers need to trade in the underlying S&P 500 index to remain delta-hedged during an equity market crash? To answer this question, I estimate dealers' liquidity demand as

$$\widehat{LiqDemand}_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times \left[\widehat{\Delta}_{t+1}^i - \Delta_t^i\right] \times SPX_t \tag{6}$$

where $\widehat{LiqDemand}_{t+1}$ is the estimated dollar trading volume that would keep dealers' option positions delta-hedged, $NetPosition_t^i$ is dealers' net position in option i at the end of day t as estimated in section IV, $\hat{\Delta}_{t+1}^i$ is the estimated delta of option i and SPX_t is the value of the S&P 500 index. Δ_t^i is options' Black-Scholes-Merton delta, with σ_t^i set equal to the options' Black-Scholes-Merton implied volatility. $\widehat{\Delta}_{t+1}^i$ is estimated as options' Black-Scholes-Merton delta, where $\sigma_{t+1}^i = \sigma_t^i$ and $SPX_{t+1} = SPX_t \times \mu$ and μ takes values of [0.85, 0.9, ..., 1.15] to simulate S&P 500 returns of $[-15\%, -10\%, ..., 15\%]$.

Dealers' liquidity demand for the adjustment of delta-hedges amounts to billions of dollars. Figure 8 shows the estimated dealer liquidity demand from equation 6 for different hypothetical returns of the underlying S&P 500 index. The figure shows that, given dealers' option positions, if the underlying index experiences a -10% return, dealers' would need to sell about $20bn worth of equities to remain delta hedged. This liquidity demand far exceeds typical trade volumes in equities and futures between 20:00 and 04:00. As a result, dealers face large constraints on their hedge adjustments over night periods, exposing them to significant inventory risk.

The estimation of dealers' liquidity demand likely provides a lower bound. Investor demand for puts likely leads to dealer short positions in options beyond S&P 500 options, which are the focus of this study. In addition, options' delta increases in the expected volatility of the underlying and expected volatility usually spikes in times of large negative equity market returns.

VII. The Effect of Equity Liquidity on the Option Risk Premium

This section exploits the increase in overnight equity trading around 2006, to study the impact of equity liquidity on option risk premia. I show that substantial overnight equity trading emerged only around 2006, when Nasdaq and Nyse acquired major electronic communication networks, which presents an opportunity for a difference-in-differences estimation: Intra-week option risk premia are substantially reduced relative to weekend risk premia after the emergence of overnight equity trading.

VII.A. The Growth of Overnight Equity Trade Volumes

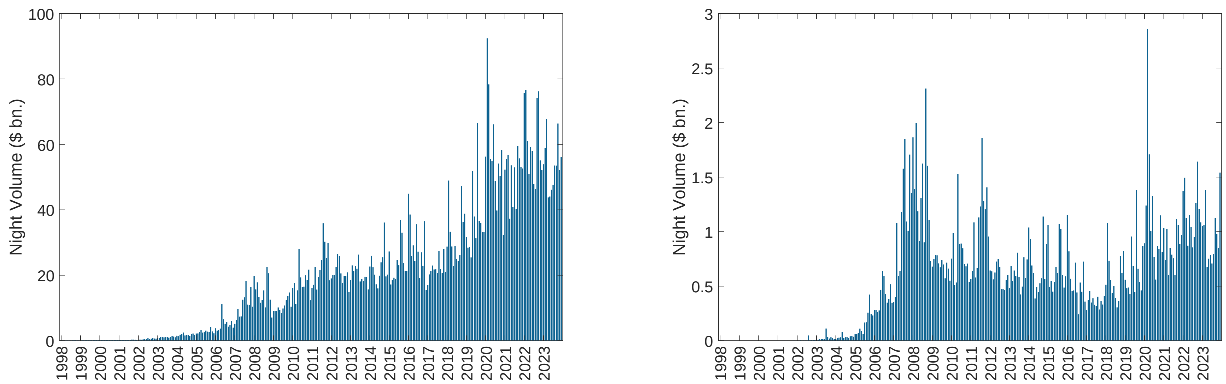
Equity trade volume was not always meaningfully higher over week-nights relative to weekends. S&P 500 E-mini futures were introduced in 1996, with trading hours close to 24 hours a day from Sunday evening to Friday evening. Yet, overnight volumes remained low until the mid 2000s. Figure 9 illustrates the emergence of overnight equity trading. Panel (a) shows the monthly average of the overnight dollar trading volume of the most liquid S&P 500 E-mini futures contract. Panel (b) shows the monthly average of the overnight dollar trading volume of the S&P 500 SPY ETF. Both volume series take off only around 2006. While the ETF volume is low relative to the futures volume, it is still a relevant series to examine, since the emergence of overnight ETF trading signals the emergence of overnight stock trading, with significant volume at least in large-cap stocks. Above, I describe the evolution of overnight U.S. equity trading and link the emergence of significant volumes around 2006 to the acquisition of the major electronic communication networks by the major U.S. equity exchanges (Nasdaq and Nyse).

The sharp increase in overnight equity trade volume relative to over-weekend trade volume offers a rare opportunity to study the effects of market liquidity on asset risk premia. If equity liquidity affects option risk premia, then week-night option risk premia should decline relative to weekend option risk premia around the emergence of week-night equities trading. Unfortunately, high-frequency options data for the late 90s and early 2000s are either unavailable or illiquid. Thus, I take a different approach, that uses widely available options data and circumvents the issue of potentially biased intraday option returns over the low-liquidity sample.

VII.B. The Change in Option Risk Premia

In order to study option risk premia around the emergence of overnight equity trading, I compare intra-week option returns to weekend option returns. Weekend returns are measured from Friday 16:15 to Monday 16:15, intra-week returns comprise of all other daily close-to-close returns. Returns are delta-hedged at the beginning of the respective period. Intra-week returns constitute the treatment group, since they include the weeknight periods where equity trading emerged, and weekend returns constitute the control group, since they include fewer such periods. Weekend returns do include the period of Sunday evening to Monday morning where equity trading grew substantially too. My identification relies on intra-week returns being treated more than weekend

Figure 9: S&P 500 Night Trade Volume Became Meaningful Around 2006



(a) Futures (b) ETF

Note: Panel (a) shows the monthly average of the overnight trade volume in the most liquid S&P 500 E-mini futures contract. Panel (b) shows the monthly average of the overnight trade volume in the S&P 500 SPY ETF. Overnight trade volume is measured between 16:00 and 09:30 and displayed in billion dollars.

returns, since the former include substantially more periods where equity trading emerged.

I estimate the following regression specification:

$$R_t^i = \beta_1 \, IntraWeek_t + \beta_2 \, Post_t + \beta_3 \, IntraWeek_t \times Post_t + \epsilon_t^i \tag{7}$$

where R_t^i is the average option return over day t, $IntraWeek_t$ is a dummy for close-to-close returns that are not Friday to Monday, $Post_t$ is a dummy for the period after treatment. Since the emergence of overnight equity trading cannot be attributed to any specific year, I provide regression estimates with post dummies between 2004 and 2010.

Data: Option Returns Intra-Week and Weekend. I obtain daily option data from OptionMetrics, which is the standard dataset for option pricing research. OptionMetrics aggregates option trades at the daily frequency, such that all available observations are at 16:15. I obtain option's bid quote, ask quote, and delta. While OptionMetrics applies a proprietary method for calculating options' deltas, their deltas are typically close to Black-Scholes deltas where sigma is set equal to the options implied volatility. To alleviate concerns of liquidity and data errors, I apply several filters to the data. I exclude options with a zero trade volume on any of the previous three days. I discard options with negative lagged bid-ask spreads, lagged bids of 0, lagged mid quotes below \$0.05 or lagged spreads above \$10. I discard large hedged or un-hedged reversal returns (returns above 1000% immediately followed by −90% or vice versa). Finally, I discard

Table VIII: Intra-Week Option Returns are Reduced after the Growth of Overnight Equity Trading

	('03)	('04)	('05)	('06)	('07)	('08)	('09)
IntraWeek	101.2	45.4	78.2	127.2	166.5*	268.6***	292.8***
	(0.84)	(0.41)	(0.77)	(1.37)	(1.92)	(3.09)	(3.30)
Post	-411.4***	-448.2***	-400.9***	-349.5***	-324.6***	-257.7**	-287.6**
	(-3.04)	(-3.45)	(-3.18)	(-2.83)	(-2.64)	(-2.07)	(-2.25)
IntraWeek x Post	468.9***	571.6***	553.2***	507.0***	471.7***	321.6**	298.5**
	(3.18)	(4.04)	(4.03)	(3.76)	(3.51)	(2.35)	(2.13)
Constant	-266.9**	-256.0**	-303.9***	-350.7***	-377.9***	-427.6***	-421.3***
	(-2.42)	(-2.52)	(-3.27)	(-4.12)	(-4.77)	(-5.73)	(-5.45)
Observations	6,958	6,958	6,958	6,958	6,958	6,958	6,958
R2-adjusted	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Note: This table shows that, relative to weekend risk premia, intra-week risk premia are reduced after the emergence of overnight equity trading. The table presents regression estimates of Equation 7, where option returns are regressed on a dummy for intra-week returns, a dummy for the period post emergence of overnight equity trading, and an interaction of the two. Option returns are for the portfolio of deep out-of-the-money, short-maturity S&P 500 put options. Weekend returns are measured from Friday 16:15 to Monday 16:15, intra-week returns comprise of all other daily close-to-close returns. Column '03 ('04, etc.) set the treatment dummy in 2003.01 (2004.01, etc.). Returns are in basis points and are delta-hedged at the beginning of the respective period. The sample period is 1996 to 2023.

observations that violate no-arbitrage bounds.

Intra-week option risk premia are reduced relative to weekend option risk premia around the introduction of week-night equity trading. Table VIII shows regression estimates of equation 7, where the left-hand-side option return is the average return for out-of-the-money, short-maturity S&P 500 put options. Column (1) shows that the average weekend return before 2003 was -267 basis points and intra-week returns were higher by 101 bps, tough not significantly different. After 2003 the average weekend put return is reduced by -411 bps, while average intra-week put returns show a relative increase of 469 bps. The crucial coefficient for the diff-in-diff setup is the interaction of treatment group dummy "IntraWeek" with treatment dummy "Post", which shows relatively reduced (i.e. less negative) option risk premia over periods where equity trade volume increased. For robustness, the subsequent columns repeat the estimation for Post dummies in 2004.01 to 2009.01. Across columns, intra-week option risk premia are significantly reduced relative to weekend risk premia after the treatment.

These results suggest an impact of equity liquidity on option risk premia, likely through dealers' inventory risk. As I argue in this paper, dealers' inventory risk is related to equity liquidity, since low equity trade volumes impede dealers' ability to continuously adjust their inventory delta-hedges. Hu, Kirilova, and Muravyev (2023) study Korean data and find that few option dealers engage in delta-hedging. In contrast, my results suggest that delta-hedging is an important part of option dealers risk-management in U.S. markets.

The increase in weekend risk-premia over the Post period that is visible in the second row of the table is possibly caused by the 2008 Global Financial crisis that occurred immediately after the emergence of weeknight equity trading. Risk-premia across asset classes were substantially suppressed ahead of the 2008 GFC and the increase in weekend option risk premia after 2008 possibly reflects increased investor attention to risk.

Figure 2 illustrates the change in intra-week option risk premia around the emergence of week-night equity trading. The figure plots the cumulative log returns of out-of-the-money short-maturity S&P 500 puts over intra-week and weekend periods. Returns are scaled to the same 10% annualized volatility. Cumulative scaled log returns of out-of-the-money puts are remarkably similar before the emergence of week-night equity trading around 2006, which is indicated with the vertical line. Afterwards a large and persistent gap emerges between the two cumulative return series.

VIII. Conclusion

This paper suggests that S&P 500 option risk premia largely result from the combination of options demand and overnight equity illiquidity, which expose risk-averse intermediaries to unhedgeable inventory risk. I show that S&P 500 option risk premia are on average insignificant intraday, but significantly negative overnight, outside of regular exchange trading hours. Dealers' inventory exposure to overnight equity price gaps can explain this finding. Dealers have a net-short position in put options, which exposes them to overnight equity "gap risk", the risk that equity prices change overnight, since overnight equity liquidity is too low for continuous delta-hedging. In contrast, intraday equity liquidity presents few such obstacles. Supporting this channel, the emergence of overnight equity trading around 2006 leads to a relative reduction in option risk premia over parts of the week that include more overnight trading sessions, suggesting a causal effect of equity liquidity on option risk premia, likely through dealers' inventory risk.

My results have three implications. (i) Option risk premia vary with the liquidity of the underlying asset. Not all options should be expected to have insignificant intraday risk premia, since most underlying assets are not as liquid intraday as the S&P 500. Similarly, significant intraday S&P 500 option risk premia might still arise in times of reduced liquidity or exceptional (jump) risk. (*ii*) Security market design has a large impact on option risk premia and regulators who want to lower hedging costs for option market customers should consider the potentially beneficial impact of around-the-clock market liquidity. (*iii*) My results suggest that investor demand for options translates into option risk premia only insofar as it exposes dealers to unhedgeable risk. As a result, option risk premia likely reflect a combination of the investor pricing kernel and the intermediary pricing kernel.

References

Aleti, Saketh, and Tim Bollerslev, 2024, News and asset pricing: A high-frequency anatomy of the sdf, *The Review of Financial Studies* p. hhae019.

Amihud, Yakov, and Haim Mendelson, 1980, Dealership market: Market-making with inventory, *Journal of Financial Economics* 8, 31–53.

Andersen, Torben, Ilya Archakov, Leon Grund, Nikolaus Hautsch, Yifan Li, Sergey Nasekin, Ingmar Nolte, Manh Cuong Pham, Stephen Taylor, and Viktor Todorov, 2021, A descriptive study of high-frequency trade and quote option data, *Journal of Financial Econometrics* 19, 128–177.

Andersen, Torben G, Nicola Fusari, and Viktor Todorov, 2015, The risk premia embedded in index options, *Journal of Financial Economics* 117, 558–584.

——— , 2017, Short-term market risks implied by weekly options, *The Journal of Finance* 72, 1335–1386.

Augustin, Patrick, Ing-Haw Cheng, and Ludovic Van den Bergen, 2021, Volmageddon and the failure of short volatility products, *Financial Analysts Journal* 77, 35–51.

Bakshi, Gurdip, Cao Charles, and Zhiwu Chen, 1997, Empirical performance of alternative option pricing models, *Journal of Finance* 52, 2003–2049.

Bakshi, Gurdip, and Nikunj Kapadia, 2003, Delta-hedged gains and the negative market volatility risk premium, *The Review of Financial Studies* 16, 527–566.

Baltussen, Guido, Julian Terstegge, and Paul Whelan, 2024, The derivative payoff bias, *Working Paper.*

Bates, David S., 2022, Empirical option pricing models, *Annual Review of Financial Economics* 14, 369–389.

Black, Fischer, and Myron Scholes, 1973, The pricing of options and corporate liabilities, *Journal of Political Economy* 81, 637–654.

Bogousslavsky, Vincent, 2021, The cross-section of intraday and overnight returns, *Journal of Financial Economics* 141, 172–194.

Bollen, Nicolas P.B., and Robert E. Whaley, 2004, Does net buying pressure affect the shape of implied volatility functions?, *Journal of Finance* 59, 711–753.

Bollerslev, Tim, and Viktor Todorov, 2011, Tails, fears, and risk premia, *Journal of Finance* 66, 2165–2211.

Boyarchenko, Nina, Lars C Larsen, and Paul Whelan, 2023, The overnight drift, *The Review of Financial Studies.*

Brunnermeier, Markus K., and Lasse Heje Pedersen, 2009, Market liquidity and funding liquidity, *Review of Financial Studies* 22, 2201–2238.

Cao, Jie, and Bing Han, 2013, Cross section of option returns and idiosyncratic stock volatility, *Journal of Financial Economics* 108, 231–249.

Chen, Hui, Scott Joslin, and Sophie Xiaoya Ni, 2019, Demand for crash insurance, intermediary constraints, and risk premia in financial markets, *The Review of Financial Studies* 32, 228–265.

Christoffersen, Peter, Bruno Feunou, Yoontae Jeon, and Chayawat Ornthanalai, 2021, Time-varying crash risk embedded in index options: The role of stock market liquidity, *Review of Finance* 25, 1261–1298.

Coval, Joshua D., and Tyler Shumway, 2001, Expected option returns, *Journal of Finance* 56, 983–1009.

Cuesdeanu, Horatio, and Jens Carsten Jackwerth, 2018, The pricing kernel puzzle: Survey and outlook, *Annals of Finance* 14, 289–329.

Dew-Becker, Ian, and Stefano Giglio, 2023, Risk preferences implied by synthetic options, *NBER Working Paper.*

——— , Anh Le, and Marius Rodriguez, 2017, The price of variance risk, *Journal of Financial Economics* 123, 225–250.

Du, Du, 2011, General equilibrium pricing of options with habit formation and event risks, *Journal of Financial Economics* 99, 400–426.

Garleanu, Nicolae, Lasse Heje Pedersen, and Allen M. Poteshman, 2009, Demand-based option pricing, *The Review of Financial Studies* 22, 4259–4299.

Goyenko, Ruslan, and Chengyu Zhang, 2019, Demand pressures and option returns, *Working Paper.*

Grossman, Sanford J, and Merton H Miller, 1988, Liquidity and market structure, *the Journal of Finance* 43, 617–633.

Gruenthaler, Thomas, 2022, Risk premia and option intermediation, *Working Paper.*

Hendershott, Terrence, Dmitry Livdan, and Dominik Rösch, 2020, Asset pricing: A tale of night and day, *Journal of Financial Economics* 138, 635–662.

Heston, Steven L, and Karamfil Todorov, 2023, Exploring the variance risk premium across assets, *Working Paper.*

Hitzemann, Steffen, Michael Hofmann, Marliese Uhrig-Homburg, and Christian Wagner, 2021, Margin requirements and equity option returns, *Working Paper.*

Hu, Jianfeng, Antonia Kirilova, and Dimitry Muravyev, 2023, Option market makers, *Working Paper.*

Hull, John, 2022, *Options, Futures and Other Derivatives, 11th* (Pearson).

Johannes, Michael S, Andreas Kaeck, and Norman Seeger, 2023, Fomc announcement event risk, *Working Paper.*

Jones, Christopher S., and Joshua Shemesh, 2018, Option mispricing around nontrading periods, *Journal of Finance* 73, 861–900.

Kanne, Stefan, Olaf Korn, and Marliese Uhrig-Homburg, 2023, Stock illiquidity and option returns, *Journal of Financial Markets* 63, 100765.

Lemmon, Michael, and Sophie Xiaoyan Ni, 2014, Differences in trading and pricing between stock and index options, *Management Science* 60, 1985–2001.

Merton, Robert C., 1973, Theory of rational option pricing, *Bell J Econ Manage Sci* 4, 141–183.

Muravyev, Dmitriy, 2016, Order flow and expected option returns, *Journal of Finance* 71, 673–708.

——— , and Xuechuan (Charles) Ni, 2020, Why do option returns change sign from day to night?, *Journal of Financial Economics* 136, 219–238.

O'hara, Maureen, and George S Oldfield, 1986, The microeconomics of market making, *Journal of Financial and Quantitative analysis* 21, 361–376.

Orłowski, Piotr, Paul Schneider, and Fabio Trojani, 2024, On the nature of (jump) skewness risk premia, *Management Science* 70, 1154–1174.

Sheikh, Aamir M, and Ehud I Ronn, 1994, A characterization of the daily and intraday behavior of returns on options, *The Journal of Finance* 49, 557–579.

Stoll, Hans R, 1978, The supply of dealer services in securities markets, *The Journal of Finance* 33, 1133–1151.

Appendix

Section A.1 provides a summary of data sources and variable construction, section A.2 contains further details on the S&P 500 options market, section A.3 contains further details on the S&P 500 equity market and section A.4 contains further details regarding option pricing theory. Sections A.5 and A.6 contain supplementary tables and figures.

A.1. Data Summary

The main paper introduces data wherever they are first used and does not contain a separate data section. Instead, I provide a summary of data sources and variable construction here.

S&P 500 Futures. I obtain data on S&P 500 E-Mini Futures from Boyarchenko, Larsen, and Whelan (2023), who follow standard practices in sampling the most liquid daily contract.

S&P 500 Options: High-Frequency. I obtain options data from the Chicago Board Options Exchange (CBOE). The dataset aggregates options trades at the 15 minute frequency such that the first available observation is at 09:45 (E.T.), 15 minutes after the regular options market open, and the last available observation is at 16:15, at the regular options market close. For each of these intervals the dataset provides option's bid quote, ask quote, and first-, last-, high- and low-trade price. Further, the dataset provides option's volume, open interest and pre-calculated risk measures like Delta, Gamma and Vega.

To alleviate concerns of liquidity and data errors I apply several filters to the data. I exclude options with either a zero trade volume on any of the previous three days or a zero trade volume at the start of the respective return period. I.e. to be included in the night (day) portfolio an option needs to be traded for three consecutive days and be traded between 16:00 and 16:15 (09:30 and 09:45)) prior to the return period. I discard options with negative lagged bid-ask spreads or zero lagged bids or lagged mid quotes below \$0.05. I discard large hedged or unhedged reversal returns (returns above 1000% immediately followed by -90% or vice versa). Finally, I discard observations that violate no-arbitrage bounds. These steps are similar to those in Jones and Shemesh (2018) and Muravyev and Ni (2020).

I measure night returns from 16:15 to 09:45 (E.T.) and day returns from 09:45 to 16:15. The SPX options market opens for regular trading on the CBOE at 09:30 and closes at 16:15 (E.T). I measure open prices at 09:45 since my dataset groups options data into 15 minute intervals. Throughout the paper I use mid-quotes to measure prices. I delta-hedge option returns with S&P 500 E-Mini futures at the start of the respective period, i.e. the delta-hedge for e.g. night returns is set up at 16:15 and subsequently not adjusted. Throughout the paper, I estimate options' delta via the Black-Scholes-Merton pricing formula with sigma equaling the options' implied volatility.

S&P 500 Options: Daily. I obtain daily option data from OptionMetrics, which is the standard dataset for option pricing research. OptionMetrics aggregates option trades at the daily frequency, such that all available observations are at 16:15. I obtain option's bid quote, ask quote, and delta. While OptionMetrics applies a proprietary method for calculating options' deltas, their deltas are typically close to Black-Scholes deltas where sigma is set equal to the options implied volatility. To alleviate concerns of liquidity and data errors, I apply several filters to the data. I exclude options with a zero trade volume on any of the previous three days. I discard options with negative lagged bid-ask spreads, lagged bids of 0, lagged mid quotes below \$0.05 or lagged spreads above \$10. I discard large hedged or unhedged reversal returns (returns above 1000% immediately followed by −90% or vice versa). Finally, I discard observations that violate no-arbitrage bounds.

Delta-Hedged Option Returns (Option Risk Premia). I calculate delta-hedged option returns as

$$R_t^i = \frac{P_t^i - P_{t-1}^i \; - \; \Delta_{t-1}^i \; \times \; (SPX_t - SPX_{t-1})}{P_{t-1}^i} \tag{A.1}$$

where R_t^i is the return of option i over period t, P_t is the price of option i at the end of period t, SPX is the price of the S&P 500 index and Δ_{t-1}^i is the lagged delta of option i. Thus, the numerator consists of the dollar change in the option price minus the dollar change that can be explained by S&P 500 returns. The numerator consists of the lagged option price only. Thus, the equation is based on the assumption that traders do not require any capital to trade the S&P 500 index. This is a common approach in option pricing research and a reasonable assumption due to the wide availability of liquid futures contracts (Muravyev and Ni, 2020).

Delta. In my baseline specifications, I estimate options' delta from the Black-Scholes-Merton formula, where I set the expected volatility equal to the options' own implied volatility relative to the Black-Scholes-Merton pricing model. This approach to delta-hedging is common practice in academia. The skew in option implied volatilities that is plugged into the delta formula across strikes accounts for the fact that real-world equity market returns exhibit negative skewness and excess kurtosis, which the Black-Scholes-Merton model does not account for in itself. For that reason, traders sometimes refer to the practice of estimating BSM deltas via BSM implied volatilities as "the wrong number in the wrong model giving the right result". I lag options' implied volatility by one day to avoid biased delta estimates from the empirically negative correlation between options' implied volatility and equity market returns. For robustness, I repeat the main steps of the analysis in the appendix with the pre-calculated deltas from the CBOE.

S&P 500 Option Positions. I obtain "Open-Close Volume files" from the CBOE for the period of 2011 to 2023. These files split daily option volumes by contract (puts vs calls, expiry date and strike price), by trader group ("market maker", "broker-dealer", "firm", "customer" and "professional customer"), and by volume type (volume bought vs volume sold). Throughout the paper, I refer to market makers as "dealers".[10] S&P 500 options have a contract multiplier of 100, that is one option is written on 100 units of the underlying asset. To aid interpretability, I adjust units such that one option is linked to 1 unit of the underlying, i.e. I multiply all option volumes and positions by 100. I include all available S&P 500 options into the analysis: The standard monthly SPX options and the weekly SPXW options.

I cumulate dealers' daily net-buys of S&P 500 options into dealer positions, via

$$NetPosition_t^i = \sum_{k=1}^{t} NetBuys_k^i, \tag{A.2}$$

[10] Open-Close Volume files are available before 2011. However, over that earlier period, market makers are not separately identified, but have to be imputed as the counterparty to firms and customers. In this paper, I focus on the period from 2011 onward, because of the higher options liquidity.

where k is a time index from the beginning of my sample to the end of the current day t. I.e. dealers' $NetPosition_t^i$ in option i at the end of day t is calculated as the cumulative sum over all past daily dealer $NetBuys_t^i$. Thus, $NetPosition_t^i$ is the number of contracts of option i that dealers are long minus the number of contracts of option i that dealers are short. Since options are regularly listed and subsequently expire, this cumulation yields dealers' option inventory after a burn-in period. I choose a burn-in period of six months and thus arrive at my sample period of 2011.07 to 2023.07.

I illustrate the *Dealer Position* variable construction in figure A.13. I use the hypothetical case of a market with only two options that are sequentially listed. The hypothetical *Put 1* is first listed on 21-September-2023, where the Open-Close data could show that the Dealer sector bought 80 contracts and sold 10 contracts. Thus, *Dealer Net Buys* are 70 and since this is the options' first trade date *Cumulative Dealer Net Buys* are also 70. On the next day dealer buys might be 50, sells might be 20, yielding net buys of 30 and cumulative net buys of 100 as the sum of all past daily net buys. This process continues until the options' expiration. Columns VII to X illustrate an equivalent construction of cumulative dealer net buys for the hypothetical *Put 2*. I calculate the *Dealer Position* across options contracts as the sum of column VI and X. I calculate dealers' position with regards to some greek risk measure, for example *Dealer Delta Position*, as the weighted sum of columns VI and X, where the weights are given by the respective options' greek (here delta).

A.2. The S&P 500 Options Market

Options. Financial options are derivative contracts. They *derive* their value from the price S of an underlying asset (or "underlying"). A "call" option confers the right - but not the obligation - to buy one unit of the underlying at a pre-specified strike price K (or "strike"). A "put" option confers the right to *sell* one unit of the underlying. The buyer (seller) of an options contract is said to have a "long" ("short") position. Options that can be exercised at any time before expiry are called "American", while those that can be exercised only *at* expiry are called "European". In this paper I focus on European options, which is the dominant type on U.S. equity options markets. The owner of an option will only exercise the option if doing so confers a positive cash flow. Exercising a call option confers a positive cash flow if the price of the underlying is above the strike price of the option. As a result, a call options final payoff is $max(S-K,0)$, since the option will not be exercised if $S<K$. The reverse applies for put options, yielding a final payoff of $max(K-S,0)$. Figure A.10 illustrates the payoff profiles of call and put options.[11]

Settlement. "Exercise will result in delivery of cash on the business day following expiration. The exercise-settlement value, SET, is calculated using the opening sales price in the primary market of each component security on the expiration date. The exercise-settlement amount is equal to the difference between the exercise-settlement value and the exercise price of the option, multiplied by $100. SPXW exercise will result in delivery of cash on the business day following expiration. The exercise-settlement value is calculated using the closing sales price in the primary market of each component security on the expiration date. The exercise-settlement amount is equal to the difference between the exercise-settlement value and the exercise price of the option, multiplied by $100."[12]

[11] Further details on the mechanics of options markets are in Hull (2022).

[12] https://www.cboe.com/tradable_products/sp_500/spx_options/specifications/, accessed on June 13^{th}, 2024.

Margins. "Purchases of puts or calls with 9 months or less until expiration must be paid for in full. Writers of uncovered puts or calls must deposit / maintain 100% of the option proceeds plus 15% of the aggregate contract value (current index level x $100) minus the amount by which the option is out-of-the-money, if any, subject to a minimum for calls of option proceeds plus 10% of the aggregate contract value and a minimum for puts of option proceeds plus 10% of the aggregate exercise price amount. For calculating maintenance margin, use option current market value instead of option proceeds."[13]

Expiry Dates. The original SPX options expired once a month on that months' 3^{rd} Friday. Recently, the CBOE has successively added SPXW options with different expiry dates.[14] To reduce computing time, I restrict the study of option returns to the standard SPX options, while for options positions I consider both SPX and SPXW options. Adding SPXW option returns does not change the findings of this paper. SPX options are liquid across a broad range of strike prices, which occur every $5. Liquidity is particularly high for out-of-the-money options, which are puts (calls) with strike prices below (above) the current value of the underlying index. SPX options are European options, so they can only be exercises at expiry.

Option Dealers. The "CBOE C1 Exchange Rule Book" Rule 5.51 specifies the obligations of market makers. In particular, market makers on the CBOE C1 exchange are required to maintain a continuous two sided market in the relevant instrument during normal trading hours. The CBOE does not publish the names of their market makers. Anecdotally, option market makers are quite specialized firms, like Optiver, but potentially also more general trading firms like Jane Street and Citadel Securities, or even large investment banks like Goldman Sachs.

Option Trading Hours. Regular SPX option trading hours are 09:30 to 16:15 (E.T.). In 2015 the CBOE added a pre-market trading session from 03:00 to 09:15, and in 2021 the CBOE added a post-market trading session from 20:15 to 03:00, such that "Global Trading Hours" run from 20:15 to the following days 09:15, and "Regular Trading Hours" run from 09:30 to 16:15.

The implied volatility surface An equivalent view on the expensiveness of put options, besides the low delta-hedged returns, is the skew in the implied volatility (ivol) surface of equity index options. An options' ivol is the volatility that, if put into a pricing model, yields the current option price that is observed in the market. Hence, ivol is always relative to some option pricing model, such as the Black-Scholes-Merton model. Option traders often plot the ivol of options with different strike prices and time to expiry. This yields the ivol surface. More expensive options have higher ivols. For equity index options the ivol surface is usually highest for short-maturity out-of-the-money put options. In this paper I focus on option returns instead of implied volatilities, since returns allow for a more natural comparison between trading and non-trading periods.

A.3. The S&P 500 Equity Market

This section describes S&P 500 options' underlying asset: The S&P 500 U.S. equity index. I show that over the sample of 2011 to 2022 day and night returns are of similar magnitude, though day returns are about 30% more volatile. Importantly, I show that overnight trading volume in S&P 500 futures amounts to only about 20% of the daily total. These substantially lower night

[13] https://www.cboe.com/tradable_products/sp_500/spx_options/specifications/, accessed on June 13^{th}, 2024.

[14] Specifically, the CBOE added weekly Friday expiries in 2011.09, Wednesday expiries in 2016.02, Monday expiries in 2016.08, Tuesday expiries in 2022.04, and Thursday expiries in 2022.05.

volume in U.S. equities underlies my argument in subsequent sections that option dealers' hedging frictions are elevated over nights.

The S&P 500 Equity Index. The Standard & Poor's (S&P) 500 index is an index for the equity value of U.S. stocks with large market capitalizations. The index contains 500 stocks listed on U.S. exchanges with the largest market capitalizations across a broad range of industries. The index is 'capitalization-weighted', i.e. the component stocks are weighted according to the total market value of their outstanding shares, which is the share price times the number of shares outstanding. Thus, each component stock's price change impacts the index proportional to the stock's share of the total index market capitalization. The index concentration has recently risen, but any stock rarely makes up more than 5% of the index value.

Equity Returns. Over my sample period (2011.01 to 2022.12) S&P 500 returns during the night and day are of approximately equal magnitude. Figure A.2 illustrates this pattern. The figure shows the cumulative return of S&P 500 E-Mini futures. The blue (red) line cumulates log returns between 0945 (1615) and 1615 (0945). Returns are based on trade prices. I obtain data from Boyarchenko, Larsen, and Whelan (2023) who sample the most liquid S&P 500 E-Mini futures contract every day.

The return volatility and return skewness of S&P 500 returns is higher over days than nights. Figure A.2 shows summary statistics for the night and day returns of S&P 500 E-Mini futures. As discussed above, the distribution of day and night returns has a similar mean. However, night returns are less volatile, leading to a higher t-statistic on the return average. The return skewness too is higher for day than night returns. Thus, between 2011 and 2022, realized risk in US equity returns has - if anything - been higher for day- than night returns. This is inconsistent with an explanation where options are cheap intraday because equity crash risk is a night time phenomenon.

Equity Return Volatility S&P 500 equity index returns are more volatile over days than nights. Figure A.4 shows the monthly average of day (night) return volatilities in blue (red). The black line shows the day-to-night volatility ratio on the right hand side axis. Over the sample of 2011 to 2022 the volatility of S&P 500 equity index futures returns is higher over day periods by a factor of about 1.3. Table A.3 shows this formally.

Equity Trading Volume The trading volume in US equities is substantially lower overnight, relative to intraday, over the entire sample of 2011 to 2022. Figure A.3 shows the average daily dollar trading volume of S&P 500 E-Mini futures over day (blue) and night (red) periods. Following the above equity return analysis, I measure days from 0945 to 1615 and nights from 1615 to 0945. The average intraday E-Mini futures trading volume rises from an initial approximately 100 billion dollars to 400 billion dollars towards the end of the sample, while the average overnight E-Mini futures trading volume rises from approximately 5 billion dollars to 10 billion. Over the entire sample overnight volumes are so low as to be barely visible at the bottom of the figure. The black line shows the ratio between day and night trading volumes. This ratio is relatively stable around 25 throughout the sample and never dips below 12.

The trading volume of S&P 500 Futures is volatile and right-skewed over both day- and night periods. Table A.2 shows summary statistics for the daily dollar trading volume of S&P 500 E-Mini futures over day and night periods. The average intraday trading volume in S&P 500 E-Mini futures between 2011 and 2022 was $ 164 billion, with a standard deviation slightly below the mean and a positive skewness around 2. This is consistent with occasional large spikes in volumes during periods of crises, like March 2020. In contrast, the average overnight trading volume amounts to only $ 7 billion, with a standard deviation slightly below the mean and a right tail that is even more pronounced than for intraday volumes.

Equity Trading Hours Regarding equities, the current regular trading hours for all major U.S. exchanges are 09:30 to 16:00 (E.T.). These trading hours have been in place since 1985, when the NYSE moved the open time from 10:00. ETFs trade on the same exchanges as the underlying stocks and the trading hours are equivalent. Before the 1990s trading stocks outside of regular exchange trading hours would have required an over-the-counter transaction with a market maker over the telephone. In 1991 the Instinet trading system allowed institutional investors to trade stocks between 06:30 and 09:20. In 1998 the Nasdaq stock exchange introduced pre-market stock trading from 08:00 to 09:30 , following a regulatory decision by the SEC. In the early 2000s, the NYSE, CME, and others introduced pre-market sessions of their own.

In 1998, regulation ATS (Alternative Trading Systems) distinguished ATS from registered exchanges, and increased reporting requirements, thus prompting ECNs (Electronic Communications Networks) to merge and register as exchanges. In 2001, Archipelago Electronic Communications Network and the Pacific Exchange merged to create ArcaEx, the first totally electronic stock exchange. In 2005, NYSE Hybrid Market was launched, creating a blend of floor-based auction and electronic trading. In 2006, New York Stock Exchange became a public company and shortly thereafter acquired Archipelago ECN. In connection with this, the NYSE eliminated the open outcry system on the floor. In 2005, in order to regain the competitive advantage lost to the rise of ECNs, Nasdaq held an initial public offering and purchased Instinet shortly thereafter. In 2005.04 Nasdaq trading hours were extended from 08:00 to 18:30 to 04:00 to 18:30. In 2006.09 Nasdaq extended trading hours further to 04:00 to 20:00, thus establishing the extended stock trading hours that are valid throughout my sample.

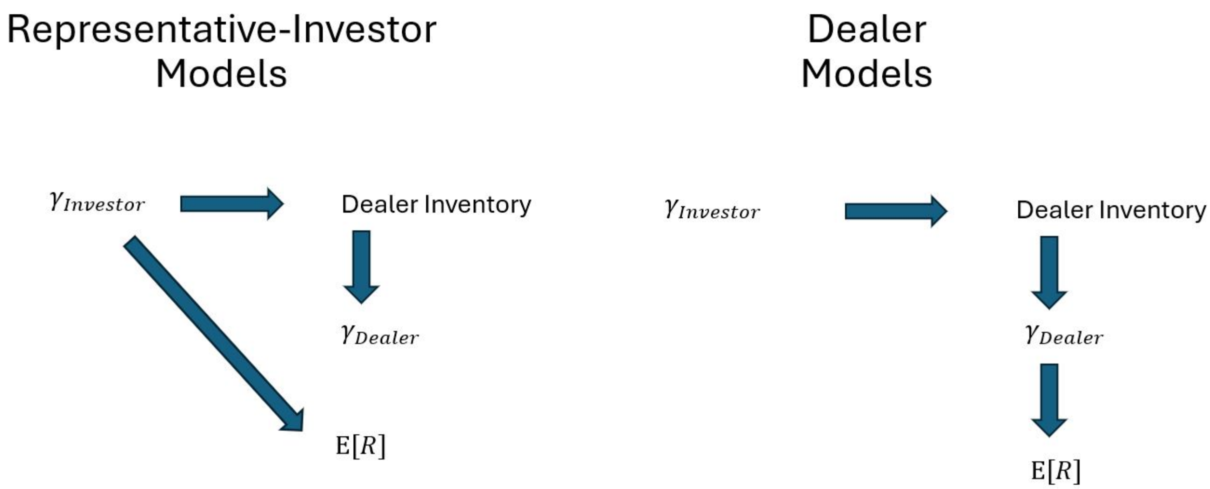
Regarding S&P 500 futures trading hours, in 1995 S&P 500 futures began trading on the CME Globex electronic exchange. Trading hours followed the major U.S. equity trading hours: 09:30 to 16:00. In 1997, S&P 500 E-Mini futures began trading on the CME Globex platform, with trading hours from Sundays at 18:00 to Fridays at 17:00 and a daily maintenance period from 17:00 to 18:00.

A.4. Option Risk Premia and Pricing Theory

This section extends on the literature around option risk premia, option pricing models and market frictions. I contrasts the two competing option pricing frameworks, "representative investor models" and "dealer models". I explain why it is difficult to test one type of model against the other and I argue that day-night variation of market liquidity presents an opportunity to overcome these difficulties.

Black-Scholes-Merton. The benchmark Black-Scholes-Merton option pricing model predicts that delta-hedged option returns equal the risk-free rate. According to standard asset pricing theory, the price of an asset is its expected payoff, discounted at some risk-adjusted rate. Black and Scholes (1973) and Merton (1973) were the first to pinn-down the discount rate for a European option. Thus, they derived the same, now famous, option pricing formula. Black and Scholes (1973) derived the formula via the Capital Asset Pricing Model. Merton (1973) applied a dynamic hedging argument. He set up a riskless portfolio of one option and Δ units of the underlying asset.

Figure A.1: Investor Preferences to Option Risk Premia Under the Two Frameworks



Note: This figure illustrates how investor preferences affect option risk premia under the two pricing frameworks. In representative-investor models, investors risk aversion affects expected option returns directly, while also affecting dealer inventory and thus dealer risk aversion. I dealer models, investor risk aversion affects expected option returns only through the impact on dealers.

Under the assumptions of no-arbitrage pricing theory this portfolio must earn the risk-free rate of return over a short period of time. Delta is the partial derivative of the option price with regards to the price of the underlying: $\frac{\partial P}{\partial U}$, where P is the price of the option and U is the price of the underlying. When the price of the underlying changes, delta changes and the riskless portfolio needs to be rebalanced to remain riskless. Hence the term *dynamic* hedging.[15] This is why I study delta-hedged option returns, where the hedge is rebalanced frequently. In addition, delta-hedging improves the statistical properties of option returns.Due to options' non-linear payoff profile, option returns are highly non-normal. This reduces the applicability of standard econometric methods, like t-statistics. Delta-hedging reduces this problem.

Representative-Investor Models. Option pricing models can be classified into two groups: "representative investor models" and "dealer models".[16] The difference between the two types of models lies in the relevance of market frictions. Agents in representative-investor models can be heterogeneous along the dimensions of beliefs and risk-aversion, but all agents have equal access to all relevant markets at all times. In particular for equity index options, equity markets and option markets are integrated in such models. As a result, the fundamental theorem of asset pricing applies to all agents and option prices reflect representative beliefs and risk-aversion. An example of this class of models is Du (2011).

Dealer Models. In dealer models only intermediaries have unconstrained access to the options market. Thus, the fundamental theorem of asset pricing applies only to option dealers and option prices reflect dealers' beliefs and risk-aversion. In these models, dealer risk exposure is typically generated as a combination of exogenous demand pressures and unhedgeable risks. For example,

[15] See Hull (2022) for further intuition and derivations.

[16] This subsection draws on the surveys by Bates (2022) and Cuesdeanu and Jackwerth (2018), as well as the discussion in Dew-Becker and Giglio (2023).

Garleanu, Pedersen, and Poteshman (2009) develop a partial-equilibrium model with exogenous option demand shocks and risk-averse dealers with fixed intermediation capacity. In their setting, dealers are exposed to unhedgeable risks because of discrete trade time, local jumps- and stochastic volatility in the underlying asset.

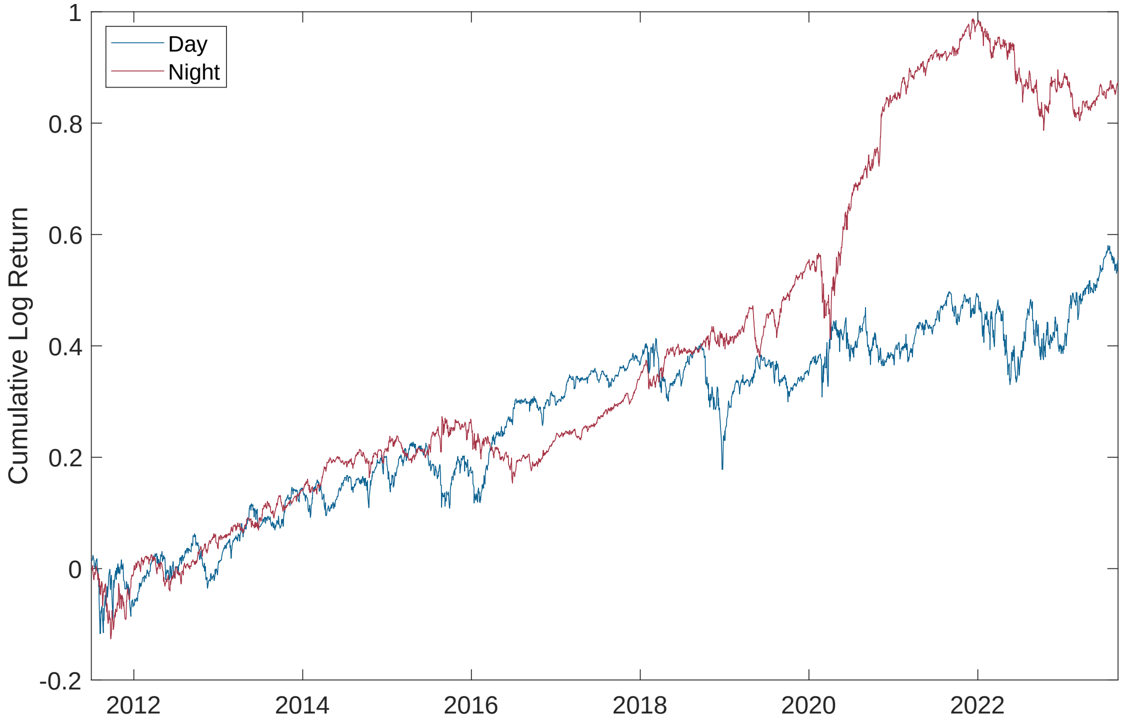
Representative-Investor Models vs. Dealer Models. It is difficult to separate the predictions of representative-investor models and dealer models. Figure A.1 illustrates how predictive power of dealer inventories for option risk premia can be consistent with either representative-investor models or dealer models. The figures' left side shows an example where only investor risk aversion $\gamma_{Investor}$ directly affects option risk premia. However, investor risk aversion also raises their demand for puts, leading to negative $DealerInventory$ and increased dealer risk aversion γ_{Dealer}. In such a setting, dealers' inventory predicts option risk premia even though intermediation does not affects asset risk premia. The figures' right side shows an example where investor risk aversion affects option risk premia only through their impact on dealer inventories, for example because regulation or market frictions prevent investors from selling options Bates (2022). Nonetheless, measures of investor risk aversion correlate with option risk premia under this framework, too. As a result, regressing option risk premia on measures of investor risk aversion or dealer inventories cannot distinguish between the two option pricing frameworks.

Variation in the hedgeability of option positions presents an opportunity to distinguish representative-investor models from dealer models. Dealer models predict elevated option risk premia over periods with elevated market frictions. Dew-Becker and Giglio (2023) work out this model implication explicitly. In this paper, I show that dealers liquidity demand for the adjustment of delta-hedges is large relative to overnight equity trade volumes. Thus, overnight market illiquidity presents a substantial hedging friction and night periods present an opportunity to distinguish representative-invenstor mdoels from dealer models, since night periods occur predictably across economic states and independent of aggregate economic risk aversion.

A recent literature addresses the endogeneity of dealer inventories and shows that intermediaries matter for option risk premia. Muravyev (2016) employs a two-stage least squares approach and regresses option returns on predicted dealer inventories. Chen, Joslin, and Ni (2019) identifying periods where dealers' trades in deep out-of-the-money puts are likely driven by tightening dealer capital constraints. These papers show that dealers matter for option risk premia. This paper shows that dealer inventory risk can fully explain option risk premia.

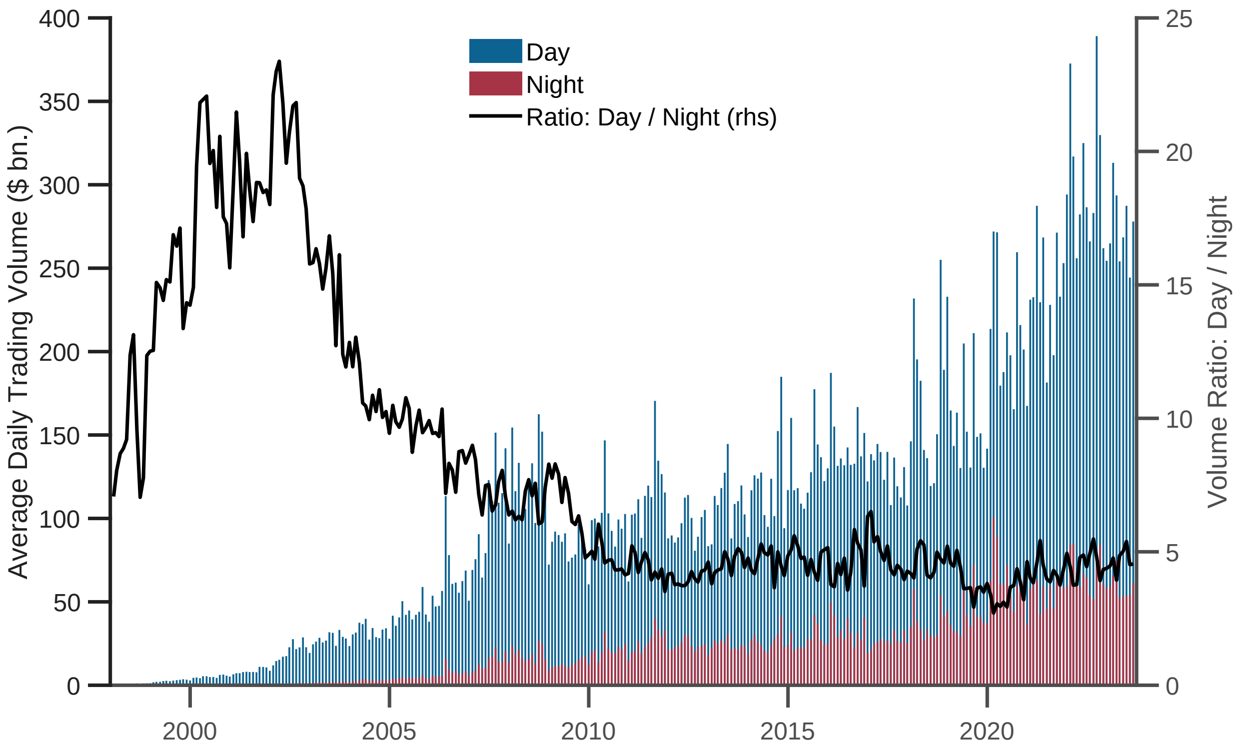
A.5. Appendix: Figures

Figure A.2: Cumulative S&P 500 Returns: Day and Night



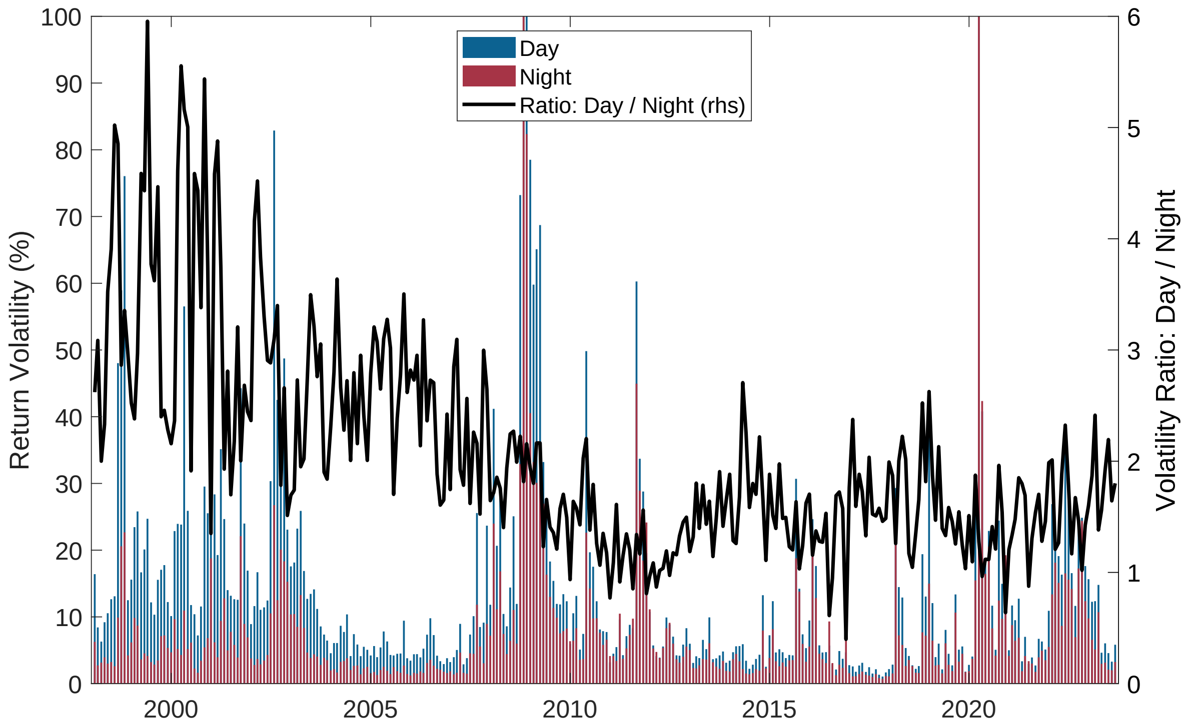
Note: This figure shows that day-returns and night-returns of the S&P 500 index are of similar magnitude over my sample. The figure shows the cumulative log return of S&P 500 E-Mini futures. The blue cumulates day returns, as measured between 0945 and 1615. The red line cumulates night returns, as measured between 1615 and 0945. Returns are in logs and are based on trade prices.

Figure A.3: S&P 500 Futures Trade Volume



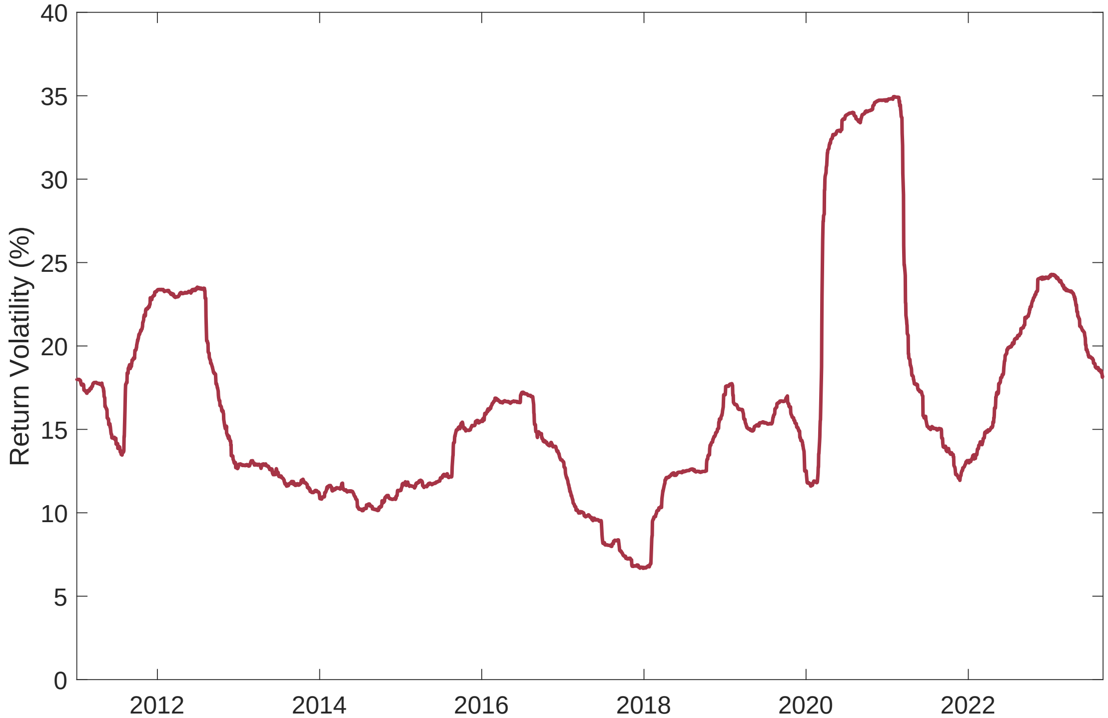
Note: This figure shows the average daily dollar trading volume of the most liquid S&P 500 E-Mini futures contract. The blue (red) line shows monthly average volumes between 0930 (1600) and 1600 (0930). The black line shows the ratio between day and night volumes. The sample period is 2011.1 - 2022.12.

Figure A.4: S&P 500 Return Volatility: Day vs. Night



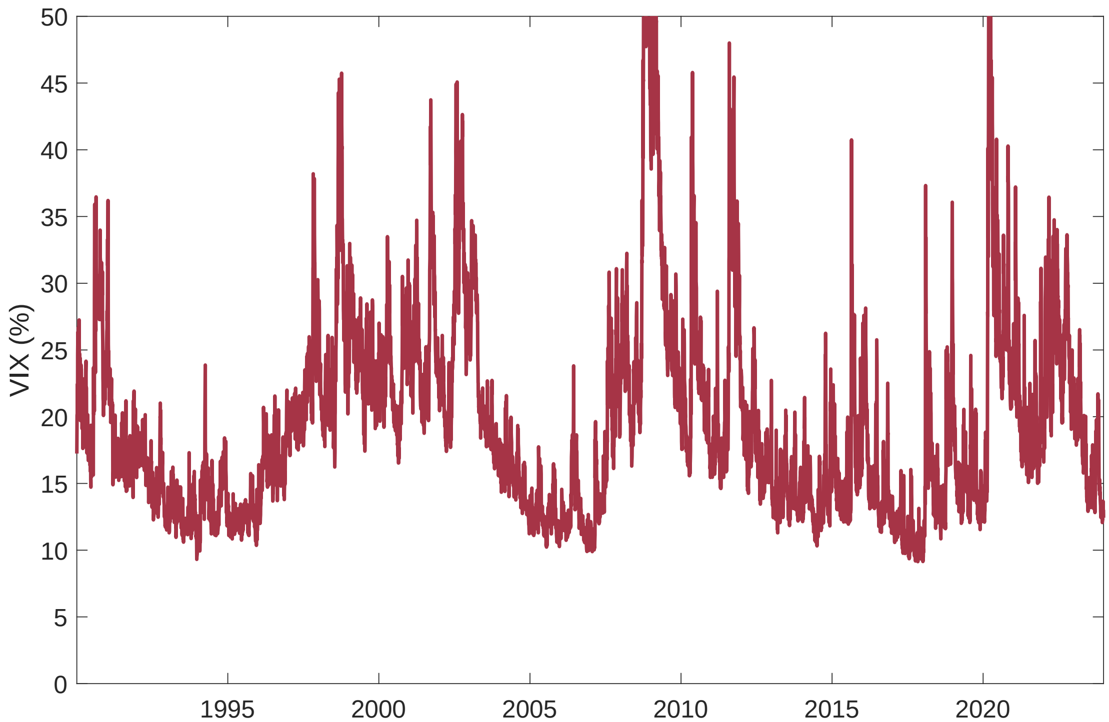
Note: This figure shows that S&P 500 returns are more volatile over day periods than night periods. The figure shows the annualized return volatility of S&P 500 E-Mini futures. Blue (red) bars show the annualized volatility of day (night) returns over the respective month. Day returns are measured between 0930 and 1600, night returns are measured between 1600 and 0930. The black line shows the ratio between day and night volatilities on the right hand scale.

Figure A.5: S&P 500 Daily Return Volatility, Rolling



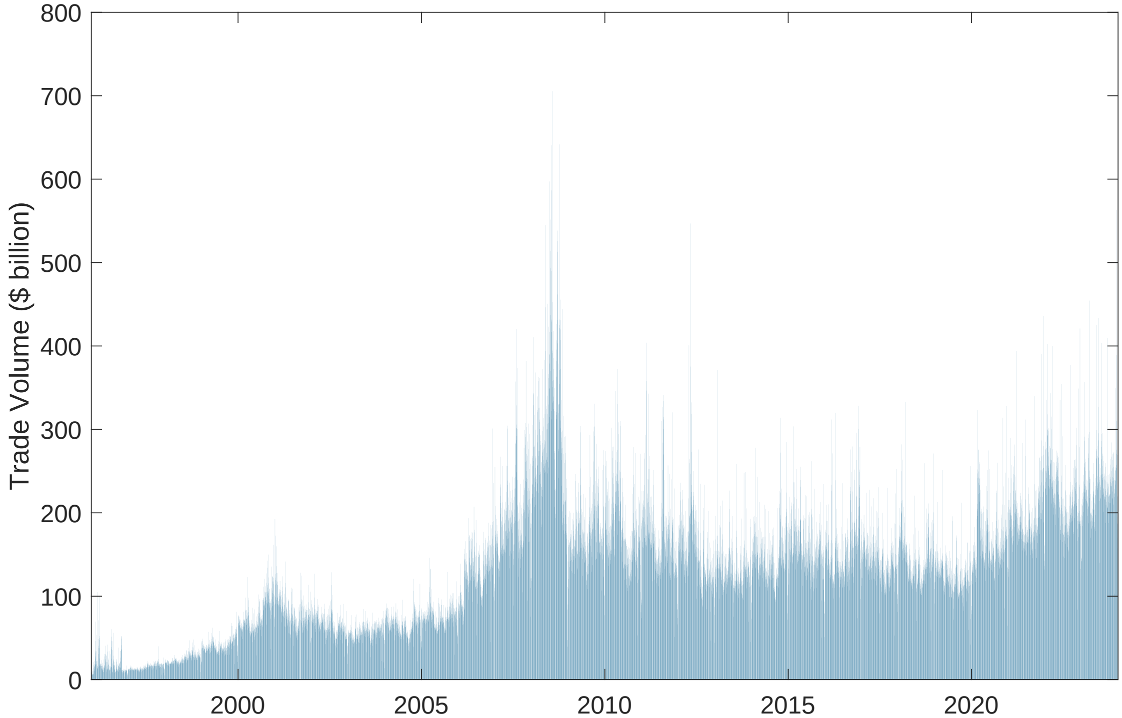
Note: This figure shows the rolling volatility of S&P 500 index returns. Returns are measured close-to-close, i.e. 16:00 to 16:00 (E.T.). Volatility is measured over a rolling 365 day window and is annualized to 252 trade days.

Figure A.6: The “VIX” Volatility Index



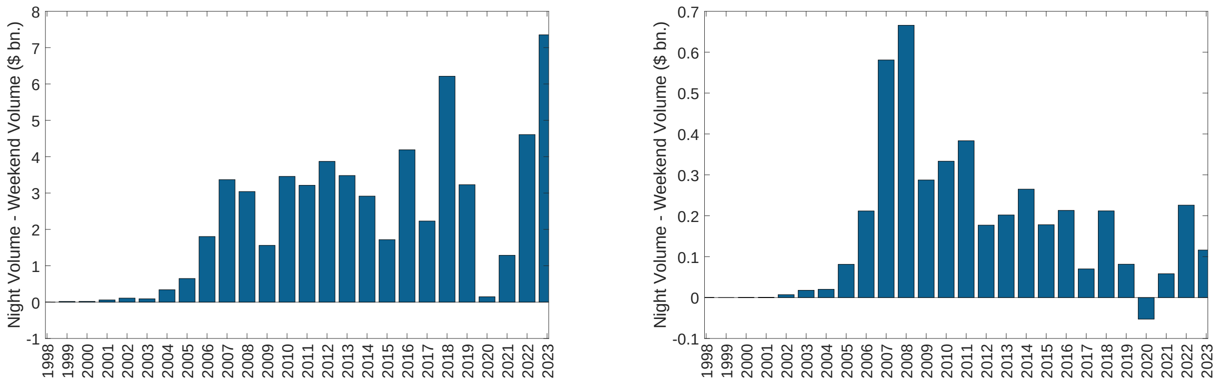
Note: This figure shows the “VIX” index for the expected volatility of S&P 500 index returns. The VIX reaches a value of 83 in March 2020.

Figure A.7: S&P 500 Equity Trade Volume



Note: This figure shows the daily trade volume of the S&P 500 constituent stocks.

Figure A.8: Overnight Volumes Increased Relative to Weekend Volumes Around 2006

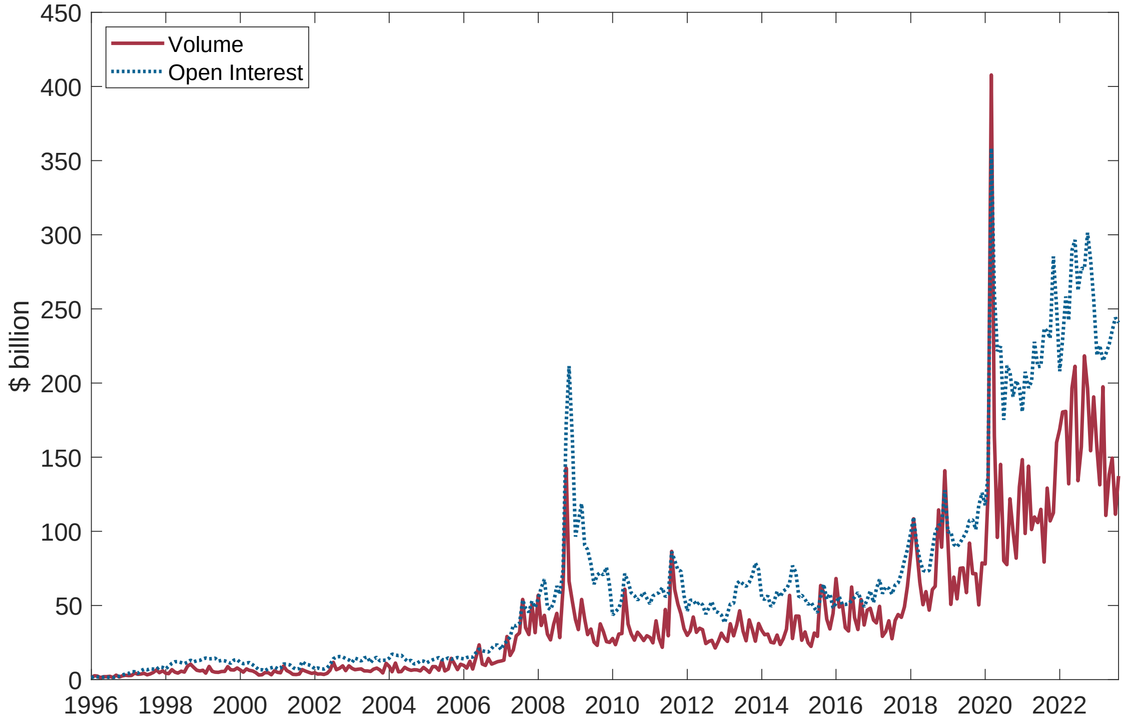


(a) Futures

(b) ETF

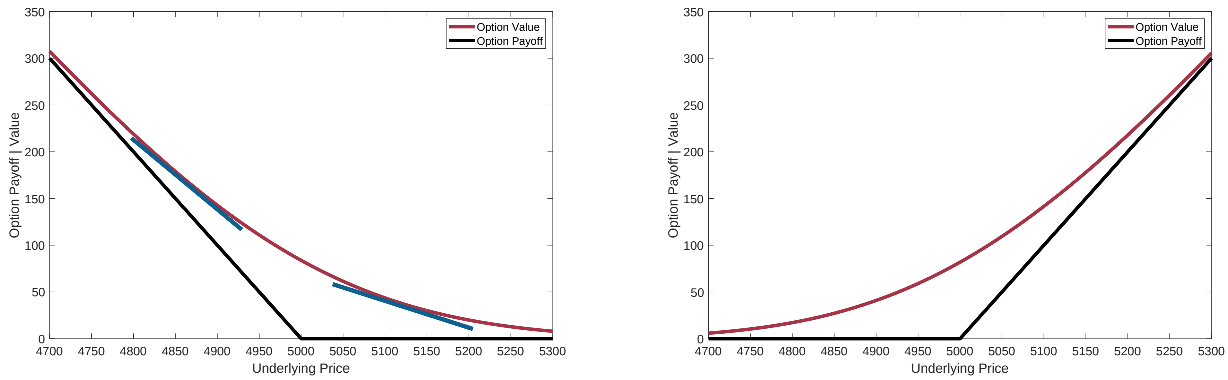
Note: This figure shows annual average night trade volumes minus annual average weekend trade volumes. Panel (a) contains the most liquid S&P 500 E-mini futures contract. Panel (b) contains the S&P 500 SPY ETF. Weekend trade volume is measured from Friday 16:00 to Monday 09:30. Night trade volume is measured from Monday 16:00 to Tuesday 09:30, etc.

Figure A.9: S&P 500 Option Market Size



Note: This figure shows that the market for S&P 500 options is large and growing. The upper dotted blue line shows S&P 500 options' average monthly dollar open interest. The lower solid red line shows S&P 500 options' monthly sum of dollar trading volume.

Figure A.10: Illustration: Option Payoff, Value and Delta

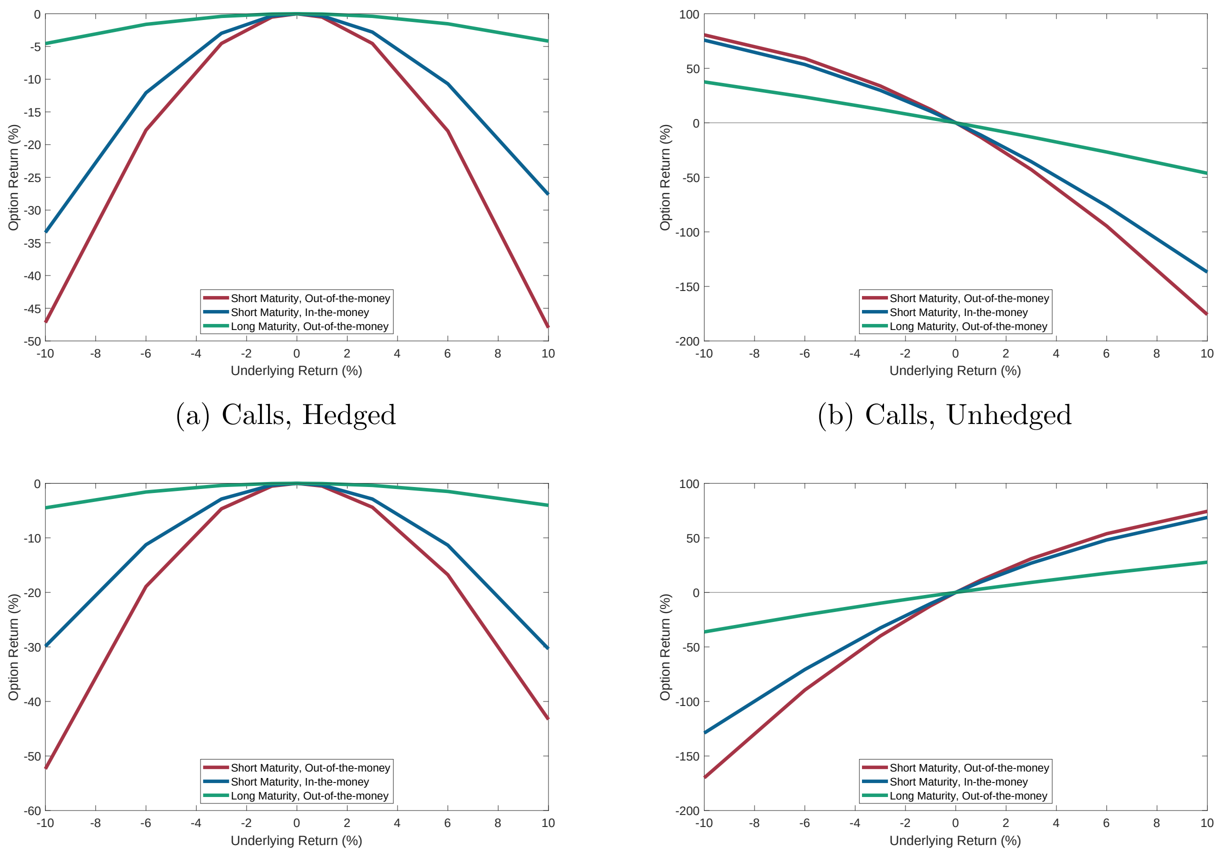


(a) Put Option

(b) Call Option

Note: This figure illustrates the payoff profile, value function and delta of put- and call option contracts. The payoff of a put option is calculated as max(K-S,0), where K is the options' strike price and S is the price of the underlying asset. Panel a plots the payoff of a put option with K=2000 as a function of S. The payoff of a call option is calculated as max(S-K,0). Panel b plots the payoff of a put option with K=2000 as a function of S.

Figure A.11: Illustration: Returns of Option Short Positions



(a) Calls, Hedged

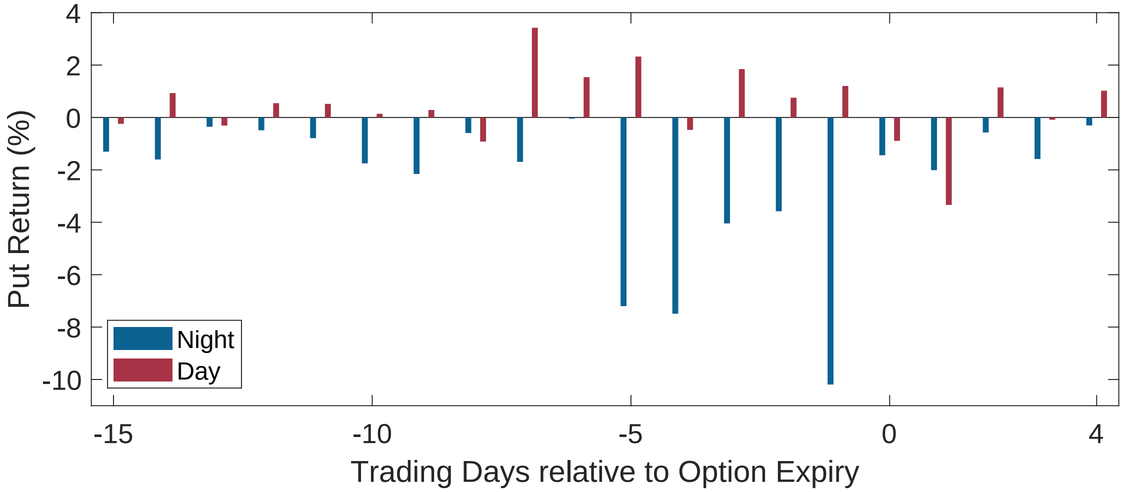
(b) Calls, Unhedged

(c) Puts, Hedged

(d) Puts, Unhedged

Note: This figure illustrates the impact of equity returns on the returns of an option short position. Panels (a), (b) contains calls, (c), (d) contain puts. Panels (a), (c) assume that the option position is initially delta-hedged, but the hedge is subsequently not adjusted. Panels (b), (d) assume unhedged options positions. Returns are simulated for option prices following Black-Scholes-Merton pricing with implied volatility $\sigma = 0.8$, risk-free rate $r = 0.03$, dividend yield $q = 0.05$ and an underlying price of $= 5000$. Short-maturity options have days to expiry $T = 7$, long maturity options have $T = 70$. Out-of-the-money puts (calls) have a strike price $K = 4900$ ($K = 5100$). In-of-the-money puts (calls) have a strike price $K = 5100$ ($K = 4900$).

Figure A.12: Option Returns Materialize During the Option Expiry Week



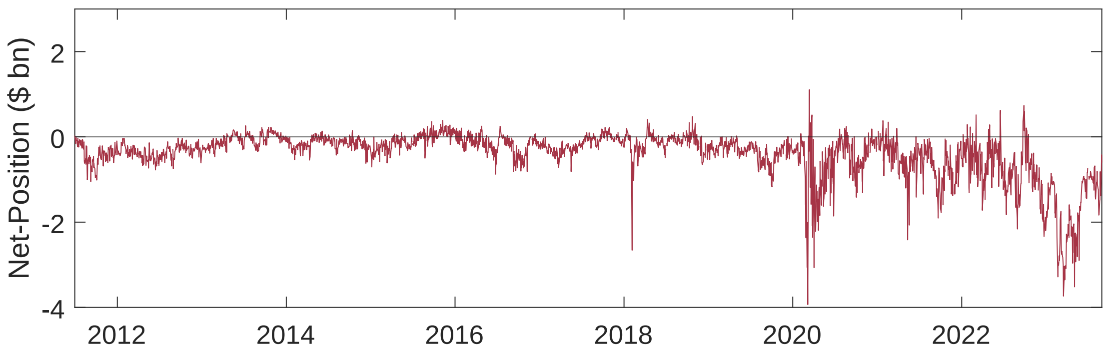
Note: This figure shows that the nagetive night returns of S&P 500 put options materialize mostly over the five days before the monthly 3^{rd} Friday option expiry. Day returns are measured from 09:45 to 16:15, night returns from 16:15 to 09:45. Returns are delta-hedged at the start of the respective period. Option returns into expiry are excluded from the sample.

Figure A.13: Variable Construction: Dealer Position

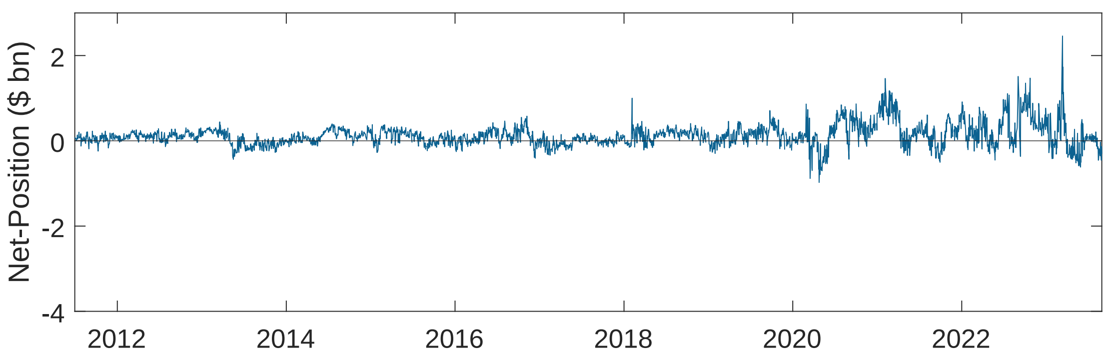
I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Weekday	Date	Put 1				Put 2				Sum Net Position
		Buys (=DB)	Sells (DS)	Net Buys (=DB-DS)	Net Position (=CDNB1)	Buys	Sells	Net Buys	Net Position (=CDNB2)	(=CDNB1 + CDNB2)
Monday	18-Sep-23									
Tuesday	19-Sep-23									
Wednesday	20-Sep-23									
Thursday	21-Sep-23	80	10	70	70					70
Friday	22-Sep-23	50	20	30	100					100
Saturday	23-Sep-23				100					100
Sunday	24-Sep-23				100					100
Monday	25-Sep-23	30	110	-80	20	40	200	-160	-160	-140
Tuesday	26-Sep-23	200	10	190	210	30	150	-120	-280	-70
Wednesday	27-Sep-23	100	100	0	210	100	100	0	-280	-70
Thursday	28-Sep-23				0	100	50	50	-230	-230
Friday	29-Sep-23				0	100	200	-100	-330	-330

Note: This figure illustrates the construction of the variable *Dealer Net-Position* from the CBOE OpenClose files. The CBOE OpenClose Volume files contain for every day and every option contract the number of contracts that dealers buy (col III) and the number of contracts sell (col IV). *NetBuys* is the number of contracts bought minus the number of contracts sold. *Net-Position* is the cumulative sum of NetBuys. The figrue is adapted from Baltussen, Terstegge, and Whelan (2024).

Figure A.14: Dealers' Net-Position in Dollars



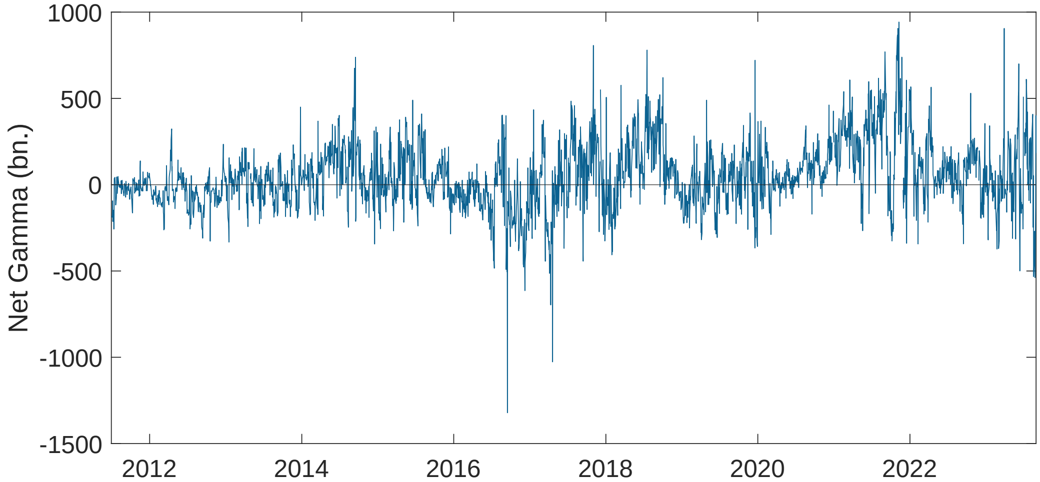
(a) Puts



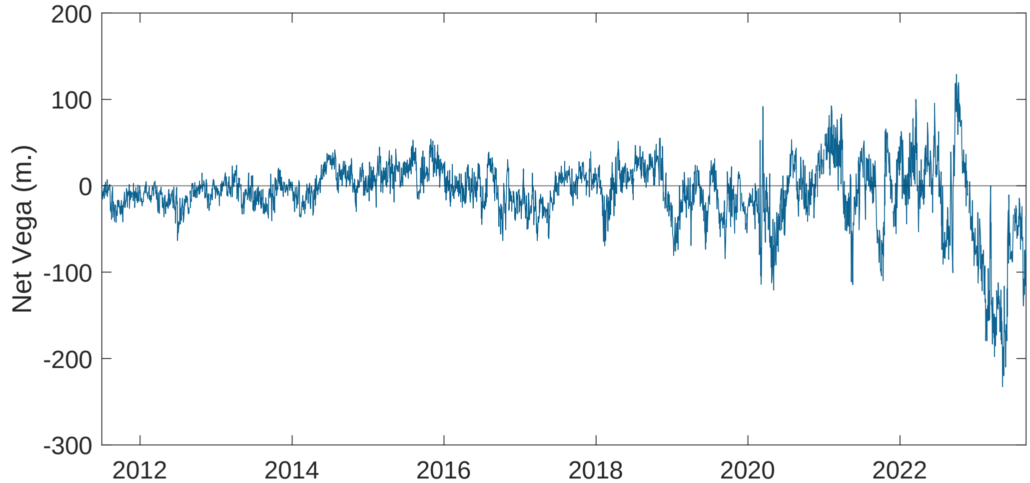
(b) Calls

Note: This figure shows dealers' dollar net-position in S&P 500 options. Panel (a) shows the daily time-series of dealers' dollar net-position in S&P 500 puts, panel (b) contains calls. Dealers' dollar net-position is the dollar value of contracts that dealers are long minus the dollar value of contracts that dealers are short. Section IV describes the variable construction.

Figure A.15: Dealers' Net-Gamma and Net-Vega



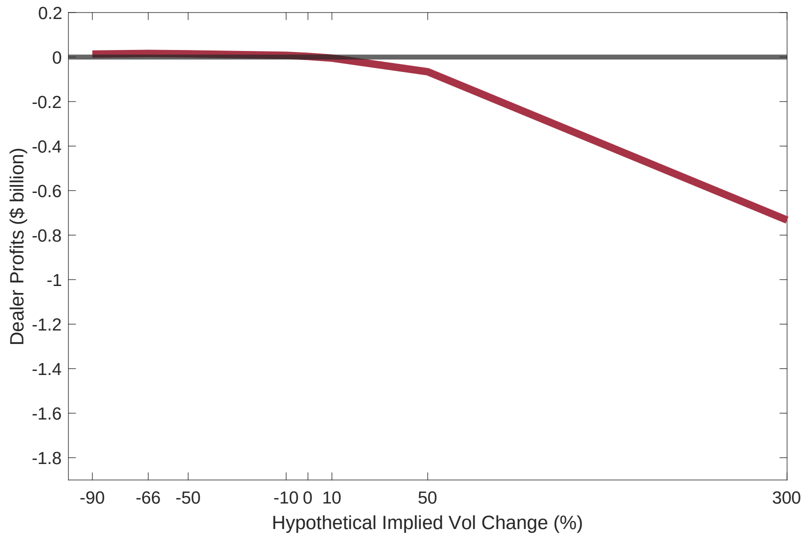
(a) Net Gamma



(b) Net Vega

Note: This figure shows option dealers' Net-Gamma and Net-Vega. Net-Gamma (Net-Vega) is the sum-product of dealers' option net-position and options gamma (vega). Gamma and Vega are from the Black-Scholes-Merton pricing model. Gamma is multiplied by the value of the S&P 500 to adjust for the increasing value of the underlying asset. Gamma is in billions, vega is in millions.

Figure A.16: Dealers' Exposure to Stochastic Volatility Risk



Note: This figure shows estimated dealer PnL for different hypothetical changes in options' implied volatilities. Dealers' option positions are equal weighted, assuming a $1 position in every option. Option returns are delta-hedged, but hedges are subsequently not adjusted. Section V describes the variable construction. The sample period is 2011 to 2023.

A.6. Appendix: Tables

Table A.1: S&P 500 Returns, Day and Night

	Mean	t-stat	Std	Skewness	Min	P1	P50	P99	Max
Day	2.14	1.64	80.54	-0.24	-513.49	-241.44	5.56	208.43	507.82
Night	3.08	2.96	63.21	-0.28	-384.38	-185.28	5.35	170.87	419.54

Note: This table shows summary statistics for returns of the S&P 500 equity index over day and night periods. Day returns are measured from 09:45 to 16:15 and night returns are measured from 16:15 to 09:45. Returns are measured from the mid-quote of E-Mini S&P 500 futures contracts. Returns are in basis points. The sample period is 2011 to 2023.

Table A.2: S&P 500 Futures Trading Volume

	Mean	Std	Skewness	P10	P50	P90
Day	169.52	84.33	1.37	87.07	146.07	290.50
Night	39.68	23.70	2.25	18.59	32.72	69.05

Note: This table shows the daily dollar trading volume of the most liquid S&P 500 E-Mini futures contract. Row 1 (2) contains volume between 0930 (1600) and 1600 (0930). Row 3 contains the sum of rows one and two. Trading volume is in billion dollars. The sample period is 2011.1 - 2022.12.

Table A.3: S&P 500 Futures Return Volatility

	Mean	Std	Skewness	P10	P50	P90
Day	11.11	27.82	11.25	1.47	4.87	23.26
Night	8.04	23.39	13.34	1.10	3.31	15.84

Note: This table shows the daily return volatility of S&P 500 E-Mini futures. Row 1 (2) contains the volatility of returns between 0930 (1600) and 1600 (0930). Volatility is annualized and in percent. The return volatility in March 2020 is winsorized at 100%. The sample period is 2011.1 - 2022.12.

Table A.4: S&P 500 Option Contract Specifications

Root	**SPX**	**SPXW**
Underlying	S&P 500	-
Expiry Date	3^{rd} Friday a.m.	any weekday, p.m.
Expiry Month	Up to 12 months	5 weeks
Last Trade Date	business day pre expiry	expiry day (1600 E.T.)
Strike Price	every 5$	-
Style	European	-
Settlement	Cash	-
Multiplier	100	-
Minimum Tick	0.05	-
Exchange	CBOE	-
Begin trading	1984	2010
Trading Hours, Regular	0930 to 1615 E.T.	-
Trading Hours, Curb	1615 to 1700 E.T.	-
Trading Hours, Global	0930 to 1615 E.T.	-

Note: This table displays the contract specifications for the standard S&P 500 index options (SPX options) and the weekly S&P 500 index options (SPXW options).

Table A.5: Option Returns, Bootstrapped Standard Errors

	Mean	S.E.	Std	Skewness	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.49	0.24	12.40	9.31	-12.66	-2.50	6.30
Day Return (%)	0.39	0.26	13.51	5.02	-10.38	-1.56	11.30
Night minus Day Return (%)	-2.88	0.38	18.48	0.62	-19.15	-1.34	11.95
Panel (b): Calls							
Night Return (%)	0.32	0.49	27.72	10.13	-16.71	-2.41	18.44
Day Return (%)	0.32	0.47	22.75	4.89	-17.03	-3.06	19.12
Night minus Day Return (%)	0.00	0.69	36.38	2.86	-28.60	0.51	25.87

Note: Panel A (B) shows summary statistics for S&P 500 put (call) option returns. Within each panel, row 1 (2) contains returns between 1615 (0945) and 0945 (1615). Returns are in excess of the risk-free rate. Returns are in percent. The sample period is 2011 to 2023.

Table A.6: Option Alphas to the Equity Return

	Mean	t-stat	Std	Skewness	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.49	-10.41	12.33	9.34	-12.39	-2.39	6.23
Day Return (%)	0.45	1.76	13.25	4.58	-10.67	-1.30	11.47
Night minus Day Return (%)	-2.94	-7.68	18.28	0.75	-19.43	-1.42	11.93
Panel (b): Calls							
Night Return (%)	0.83	1.84	25.04	11.93	-14.96	-1.12	14.67
Day Return (%)	0.49	1.13	21.18	5.84	-15.42	-2.52	17.63
Night minus Day Return (%)	0.34	0.52	33.51	2.88	-23.92	1.56	23.03

Note: Panel A (B) shows summary statistics for S&P 500 put (call) option alphas. Within each panel, row 1 (2) contains returns between 1615 (0945) and 0945 (1615). Alphas are obtained as the intercept of a univariate regression of delta-hedged option returns on contemporaneous S&P 500 futures returns. Returns are in percent. The sample period is 2011 to 2023.

Table A.7: Option Returns, Early Sample

	Mean	t-stat	Std	Skewness	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.69	-9.54	9.34	3.30	-10.91	-3.10	4.70
Day Return (%)	0.71	1.68	13.85	4.37	-10.48	-1.79	40.31
Night minus Day Return (%)	-3.39	-7.22	15.88	-1.54	-19.24	-1.51	10.91
Panel (b): Calls							
Night Return (%)	-2.71	-3.81	28.05	-0.08	-24.88	-4.22	21.39
Day Return (%)	1.08	1.10	35.79	2.43	-25.12	-3.72	97.30
Night minus Day Return (%)	-3.79	-2.91	46.44	-1.43	-42.96	-1.37	35.86

Note: Panel A (B) shows summary statistics for S&P 500 put (call) option returns. Within each panel, row 1 (2) contains returns between 1615 (0945) and 0945 (1615). Returns are in percent. The sample period is 2006 to 2011.

Table A.8: Option Risk Premia via Alternative Deltas I

	Mean	t-stat	Std	Skew	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.31	-9.38	13.05	7.71	-12.90	-3.59	8.92
Day Return (%)	-0.04	-0.13	15.61	4.29	-12.19	-3.14	43.95
Night minus Day Return (%)	-2.28	-5.66	20.19	0.22	-19.81	-0.77	14.71
Panel (b): Calls							
Night Return (%)	0.12	0.48	13.94	9.21	-9.91	-1.47	9.83
Day Return (%)	0.65	1.98	17.14	7.40	-11.71	-2.22	39.70
Night minus Day Return (%)	-0.52	-1.16	22.45	-1.81	-17.33	0.80	15.42

Note: This table shows that the main result from table I is robust to alternative approaches to calculate delta for the estimation of option risk premia. This table divides options' implied volatilities by 1.3 before calculating delta, to account for the volatility risk premium in implied volatilities. Panel (a) shows summary statistics for S&P 500 put option returns, panel (b) contains calls. Within each panel, row 1 (2) contains returns between 16:15 and 09:45 (09:45 and 16:15). Returns are in percent and in excess of the risk-free rate. Returns are delta-hedged at the beginning of the respective period. The sample period is 2011 to 2023.

Table A.9: Option Risk Premia via Alternative Deltas II

	Mean	t-stat	Std	Skew	P10	P50	P90
Panel (a): Puts							
Night Return (%)	-2.38	-10.10	12.02	10.79	-11.72	-2.52	6.33
Day Return (%)	0.22	0.90	12.91	4.69	-10.22	-1.46	31.16
Night minus Day Return (%)	-2.60	-6.94	17.70	1.37	-18.49	-1.32	11.53
Panel (b): Calls							
Night Return (%)	-0.51	-1.42	20.55	2.76	-18.60	-2.29	19.56
Day Return (%)	0.22	0.44	22.52	4.27	-19.42	-3.17	59.14
Night minus Day Return (%)	-0.73	-1.11	31.27	-1.16	-31.31	0.04	29.98

Note: This table shows that the main result from table I is robust to alternative approaches to calculate delta for the estimation of option risk premia. This table uses the CBOE pre-calculated option deltas. Panel (a) shows summary statistics for S&P 500 put option returns, panel (b) contains calls. Within each panel, row 1 (2) contains returns between 16:15 and 09:45 (09:45 and 16:15). Returns are in percent and in excess of the risk-free rate. Returns are delta-hedged at the beginning of the respective period. The sample period is 2011 to 2023.

Table A.10: The Cross-Section of Intraday Put Returns

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	58.0	-0.2	41.7
		(1.6)	(-0.0)	(1.4)
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-1.2	-1.0	-3.9
		(-0.1)	(-0.3)	(-0.3)
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	1.8	-2.0	0.9
		(0.2)	(-0.2)	(0.1)
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	4.2	22.9	4.6
		(0.3)	(1.3)	(0.3)
All		45.0	-0.7	32.9
		(1.6)	(-0.1)	(1.4)

Note: This figure shows average S&P 500 put option returns for six portfolios, sorted by days to expiry and moneyness. Returns are measured from shortly after option market open at 0945 to the subsequent market close at 1615. Returns delta-hedged and in excess of the risk-free rate. Returns are in basis points. Newey-West t-statistics are in brackets. The sample period is 2011 to 2023.

Table A.11: The Cross-Section of Intraday Call Returns

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \|\Delta\| \leq 0.25$	Deep Out of the Money	-0.5	17.8	5.0
		(-0.0)	(0.6)	(0.1)
$0.25 < \|\Delta\| \leq 0.50$	Out of the Money	4.0	8.8	2.5
		(0.3)	(0.0)	(0.2)
$0.50 < \|\Delta\| \leq 0.75$	In the Money	2.6	4.9	2.8
		(0.3)	(1.1)	(0.3)
$0.75 < \|\Delta\| \leq 1.00$	Deep In the Money	6.0	-5.8	3.0
		(0.9)	(-0.5)	(0.7)
All		39.2	24.7	35.6
		(0.8)	(1.4)	(0.9)

Note: This figure shows average S&P 500 put option returns for six portfolios, sorted by days to expiry and moneyness. Returns are measured from shortly after option market open at 0945 to the subsequent market close at 1615. Returns delta-hedged and in excess of the risk-free rate. Returns are in basis points. Newey-West t-statistics are in brackets. The sample period is 2011 to 2023.

Table A.12: The Cross-Section of Overnight Call Returns

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \|\Delta\| \leq 0.25$	Deep Out of the Money	78.0	33.6	74.6
		(0.8)	(1.1)	(0.8)
$0.25 < \|\Delta\| \leq 0.50$	Out of the Money	-3.9	-20.1	-3.2
		(-0.2)	(-3.7)	(-0.2)
$0.50 < \|\Delta\| \leq 0.75$	In the Money	-24.0	-13.3	-21.1
		(-3.1)	(-3.5)	(-3.4)
$0.75 < \|\Delta\| \leq 1.00$	Deep In the Money	-19.3	-7.7	-16.3
		(-3.1)	(-1.9)	(-3.1)
All		29.9	-2.7	20.5
		(0.6)	(-0.2)	(0.5)

Note: This figure shows average S&P 500 put option returns for six portfolios, sorted by days to expiry and moneyness. Returns are measured from option market close at 1615 to the subsequent market open at 0945. Returns delta-hedged and in excess of the risk-free rate. Returns are in basis points. Newey-West t-statistics are in brackets. The sample period is 2011 - 2023.

Table A.13: The Cross-Section of Dealers' Call Position

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-0.84	-0.50	-1.33
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	1.55	0.87	2.42
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	1.40	0.47	1.87
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	0.61	-0.01	0.59
All		2.72	0.83	3.55

Note: The table shows dealers' net position in S&P 500 call options by moneyness and days to expiry. Dealer net position is the number of contracts that dealers are long minus the number of contracts that dealers are short. Section IV describes the variable construction. Numbers are in millions. The sample period is 2011 to 2023.

Table A.14: Dealers' Equity Price Gap Risk from Calls

		Days to Expiry		
		2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-5.6	-0.6	-6.2
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	2.9	0.3	3.2
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	1.6	0.1	1.7
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	0.3	0.0	0.3
All		-0.7	-0.2	-0.9

Note: This figure shows dealers' expected PnL from a -6% return in the underlying S&P 500 index by portfolio of call options. Section V describes the variable construction. Numbers are in million dollars. The sample period is 2011 to 2023.

Table A.15: Aggregate Dealer Gap Risk: Summary Stats

	Mean	Std	Skew	P5	P50	P95
Dealer Gap Risk (*bn*)	-179.7	430.9	-5.6	-865.3	-453.6	14.8

Note: This table shows summary statistics for option dealers' inventory risk exposure to overnight equity price gaps as estimated in section V. That is, the table shows the estimated dealer Profit-and-Loss from a -5% return in the underlying S&P 500. Inventory risk is in millions of dollars. The sample period is 2011 to 2023.

Table A.16: Intra-Week Option Returns are Reduced after the Growth of Overnight Equity Trading

	('03)	('04)	('05)	('06)	('07)	('08)	('09)
IntraWeek	101.2	45.4	78.2	127.2	166.5*	268.6***	292.8***
	(0.84)	(0.41)	(0.77)	(1.37)	(1.92)	(3.09)	(3.30)
Post	-411.4***	-448.2***	-400.9***	-349.5***	-324.6***	-257.7**	-287.6**
	(-3.04)	(-3.45)	(-3.18)	(-2.83)	(-2.64)	(-2.07)	(-2.25)
IntraWeek x Post	468.9***	571.6***	553.2***	507.0***	471.7***	321.6**	298.5**
	(3.18)	(4.04)	(4.03)	(3.76)	(3.51)	(2.35)	(2.13)
Constant	-266.9**	-256.0**	-303.9***	-350.7***	-377.9***	-427.6***	-421.3***
	(-2.42)	(-2.52)	(-3.27)	(-4.12)	(-4.77)	(-5.73)	(-5.45)
Observations	6,958	6,958	6,958	6,958	6,958	6,958	6,958
R2-adjusted	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Note: This table is equivalent to table VIII, but excludes the crisis months 2008.08, 2008.09, 2009.10, 2018.02, 2020.02, 2020.04, 2020.04.