Intermediary Option Pricing*

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Abstract

I find that intermediary inventory and equity il-liquidity can explain most of the risk premium in S&P 500 options. I show that intermediaries' option inventory exposes them to "gap risk", the risk of equity price changes over periods where low equity liquidity impedes an adjustment of equity market (delta) hedges. Intermediaries' gap risk can explain why negative option returns are heavily concentrated over nights and weekends, where equity liquidity is low. Contrary to common intuition, intermediaries' inventory gamma does not capture this inventory risk. Instead, I introduce the concept of "shadow gamma", the expected option gamma in case of large negative equity market returns. Intermediaries' shadow gamma is large and negative, capturing the expected inventory losses in case of negative equity market returns, that result from intermediaries' short position in put options. I argue that gamma captures intraday risk, but shadow gamma captures overnight risk. Consistent with this argument, options' shadow gamma predicts options' night-returns, but not options' dayreturns. Finally, I exploit the increase of overnight equity trading around 2006: I find significantly less negative option returns from Mondays to Fridays, relative to option returns over weekends, after 2006. This change in the option risk premium is concentrated in options where intermediaries are short, suggesting that intermediary inventory and equity liquidity jointly drive the option risk premium.

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

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Average delta-hedged returns of S&P 500 options amount to about -0.5% a day, and these returns materialize in an increasingly large market: Open interest and trade volume in S&P 500 options have almost quadrupled between 2018 and 2023, reaching \$250bn and \$2tn p.a., respectively. The empirical findings in this paper suggest that negative option returns result largely from the combination of intermediary inventory and overnight equity il-liquidity. The economic consequences of overnight equity liquidity are particularly relevant in light of current market changes. In late 2024 and early 2025, both the NYSE and Nasdaq equity exchanges announced plans to offer close to 24-hour equity trading between Mondays and Fridays. My results suggest that higher overnight equity trade volume would help intermediaries manage their inventory risk, potentially leading to a reduction in the magnitude of the option risk premium.

A common benchmark for option returns is the Black-Scholes-Merton model, where delta-hedged returns equal the risk-free rate because a continuously adjusted stock position perfectly hedges an option on that stock.³ To explain option returns, the literature has focused on two risks that cannot be hedged with a stock positions: stochastic volatility risk, the risk of changes in expected equity return volatility, and jump risk, the risk of a discontinuous change in the equity price. However, Jones and Shemesh (2018) and Muravyev and Ni (2020) show that the negative option returns are heavily concentrated over weekends and nights, and they conclude that neither increased volatility risk nor increased jump risk can explain their findings.

In this paper, I test whether intermediary constraints can explain option returns. A concentration of option returns over nights and weekends could result from elevated intermediary inventory risk over such periods, if intermediaries (i) are the marginal seller of options, (ii) are effectively risk-averse, and (iii) bear elevated inventory risk over nights. In such a model, intermediaries would sell options at elevated prices before a night or weekend, in anticipation of the elevated inventory risk that they will have to bear from the resulting short position. The crucial questions in this argument is why inventory risk would be elevated over nights and weekends. I argue that increased overnight inventory risk results from reduced equity liquidity over such periods. Equity il-liquidity impedes intermediaries' ability to engage in the delta-hedge adjustments. Without

¹For early studies on option returns, see Coval and Shumway (2001) and Bakshi and Kapadia (2003).

³Black and Scholes (1973), Merton (1973).

delta-hedge adjustments, options quickly become exposed to equity market risk. Thus, intermediaries bear equity market risk over nights and weekends. I refer to overnight equity price risk as "gap risk". Gap risk results from options' gamma, the curvature in the option value function, which necessitates delta-hedge adjustments. Gamma is a well know risk measure in options pricing. Crucially, I show that it is not intermediaries *current* inventory gamma that describes their exposure to gap risk. Instead, intermediaries' gap risk exposure is captured by their "shadow gamma", the *expected* intermediary inventory gamma in case of large negative equity market returns.

This paper makes four contributions, using data on S&P 500 options. I show that: (i) Intermediaries' option inventory exposes them to gap risk. I estimate that, in case of an equity price crash, the intermediary sector would need to sell about \$15bn of stocks in order to remain delta-hedged. For comparison, the trade volume in the most liquid U.S. equity futures contract (the S&P 500 E-Mini) does not exceed \$300m an hour for most parts of the night. As a result, overnight equity trade volumes are not sufficient for intermediaries to dynamically adjust their delta-hedges and thus hedge their equity market risk. (ii) Intermediaries' gap risk results from options' shadow gamma. Intermediaries' inventory gamma is weakly positive, indicating inventory profits from equity price changes. In contrast, intermediaries inventory shadow gamma is large and negative, capturing the expected inventory losses in case of negative equity market returns, that result from intermediaries' short position in put options. (iii) Options' shadow gamma predicts option returns over nights (close to open) but not over days (open to close). (iv) Increasing overnight equity trade volume leads to less negative option returns. I find that the growth of overnight equity trading around 2006 led to less negative option returns from Mondays to Fridays, relative to option returns over weekends. Weekends function as the control group, since weekends contain more than 48 hours where equity and equity futures exchanges are closed, and trade volumes remained unchanged. I conclude that negative option returns are largely driven by equity il-liquidity, because equity il-liquidity exposes intermediaries to inventory gap risk, and the prospect of unhedgeable inventory risk leads intermediaries to sell options at elevated prices.

Intermediaries' option inventory exposes them to gap risk. I find that, over the period of 2011 to 2023, the intermediary sector holds a persistently negative net-position in puts, while the net-position in calls oscillates around zero. A net-position expresses the number of options intermediaries are long minus the number of options intermediaries are short. Intermediaries' net

put position amounts to about -19m contracts, indicating substantially more short positions than long positions in puts.

Due to their short position in puts, intermediaries bear gap risk. I estimate intermediaries' exposure to gap risk as the profit-and-loss from their options portfolio in case of a hypothetical -10% S&P 500 return. I assume that intermediaries initially delta-hedge their options portfolio, but subsequently cannot adjust these hedges. I estimate an average profit of -\$1.5bn in such states. Wether I assume intermediaries to be initially delta-hedged has little impact on their gap risk. The intuition for this finding is that intermediaries' option inventory is balanced against small equity returns. Exposure to equity market risk, and the need to continuously delta hedge, emerges only in case of large (negative) equity market returns. Importantly, my approach explicitly estimates 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. I show that gamma does not capture intermediaries' exposure to gap risk.⁴

Next, I estimate intermediaries' liquidity demand for the adjustment of delta-hedges, and find that in case of a -10% return in the S&P 500, intermediaries need to sell about \$15bn worth of equities in order to remain fully delta-hedged. For comparison, the average overnight volume of S&P 500 E-Mini futures amounts to less than \$300m an hour for most parts of the night. In contrast, the intraday futures trade volume exceeds \$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 il-liquidity impedes intermediaries' delta-hedging, while intermediaries face few such obstacles during regular equity trading hours.

Intermediaries' gap risk results from shadow gamma. I show that intermediaries' gap risk results from options' shadow gamma, not options current gamma, which is the common risk measure in the literature. Gamma, measures the curvature in the option value function, and, as such, measures the degree to which delta-hedges become imperfect when the price of the underlying changes. However, over my main sample from 2011 to 2023, the total gamma in intermediaries inventory oscillates around zero and is - if anything - positive. A positive inventory gamma suggests profits from equity price changes, not losses. The reason why gamma fails as a risk measure for

⁴For intuition, consider being short 10 deep-out-of-the-money puts and long one at-the-money call. This portfolio tends to experience large negative returns when stocks crash, while the aggregate gamma tends to be positive, suggesting positive returns from stock price crashes.

intermediaries' option position is that dealers' most pronounced position is a short-position in deep out-of-the-money puts, which experiences large losses in case of an equity market crash, but contributes little to intermediaries inventory gamma, since gamma is close to zero for deep-out-of-the money options. Instead, I find that intermediaries carry large negative shadow gamma. That is, intermediaries' inventory is well balanced against small equity price changes, but if the equity price changes by a large amount, then there will be inventory gamma, equity market risk and inventory losses.

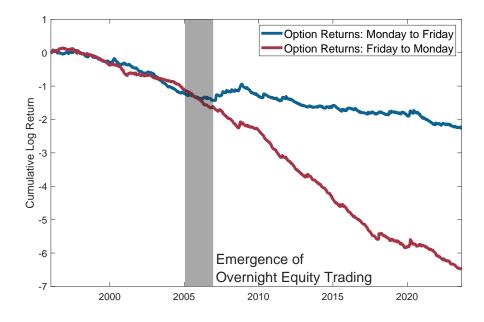
Options' shadow gamma predicts overnight option returns. I estimate option returns over days, nights and weekends. Consistent with the previous literature, I find that option returns are especially negative over weekends and nights. I find intraday option returns to not be significantly different from the risk-free rate. Thus, most of the option risk premium can be attributed to the periods (nights and weekends) when intermediaries face gap risk. 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. I show robustness of my findings to different methods for calculating delta.

The comparison between puts and calls highlights the importance of intermediary inventory risk over non-trading periods, as opposed to a general hedging friction. Both puts and calls are sold by some market participant, who then potentially faces un-hedgeable risk from market illiquidity. Yet, only puts exhibit more negative returns over nights and weekends, so only sellers of puts are compensated for increased risk. This can be explained with the intermediary short position in puts and the resulting downside intermediary gap risk.

I regress option returns on options' lagged shadow gamma, and find that shadow gamma predicts option returns over nights, but not over days. This predictability is largely driven by the high shadow gamma of out-of-the-money puts, which tend to experience the most negative average returns. The predictive power for night returns is highly significant, with t-stats exceeding 5, while there is no corresponding predictability of day returns. The option return predictability

⁵Regular 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.

Figure 1: Increasing Equity Trade Volume Lowers the Option Risk Premium



Note: This figure shows cumulative returns of 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. The Monday to Friday return is the average over the four returns between Monday close and Friday close. 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.

suggests that negative option returns compensate the seller for the risk from shadow gamma, and the elevated predictive power over nights suggests that shadow gamma derives its' importance from equity illiquidity.

Increasing equity liquidity leads to less negative option returns. Finally, I exploit the increase of overnight equity trading around 2006 to study the impact of equity liquidity on option returns. Several market changes around 2006, 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. This emergence of overnight equity trading yields a treatment group (Monday-to-Friday option returns) and a control group (Friday-to-Monday option returns). I find that around 2006 the treatment group option returns become significantly less negative, relative to the control group option returns. Figure 1 illustrates this result. A large and persistent gap emerges between the cumulative returns of S&P 500 put options Monday to Friday and Friday to Monday around the time when overnight equity trade volumes become meaningful.

These results relate to Dew-Becker and Giglio (2023), who show a decrease in the option risk premium around the Great Financial Crisis. My decomposition of option returns into a night-and weekend component suggests an explanation in the increasing liquidity of overnight equity markets.

Contribution. This paper contributes to the literature on option returns. Black and Scholes (1973) and Merton (1973) establish the risk-free rate as the benchmark for delta-hedged option returns. Coval and Shumway (2001) and Bakshi and Kapadia (2003) show that delta-hedged returns of equity index options are negative, especially for puts. Jones and Shemesh (2018) and Muravyev (2016) show that option returns are especially negative over weekends and nights, and provide explanations based on market mispricing. Jones and Shemesh (2018) show that weekend returns could be explained if investors systematically underestimate the time decay in the option value over weekends. Muravyev and Ni (2020) show that night returns could be explained if investors systematically overestimate overnight equity volatility. I show that intermediaries' exposure to gap risk can explain negative option returns, especially over weekends and nights.

This paper contributes to the 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. I find that it is the *overnight* il-liquidity of stocks that drives S&P 500 option returns, because of intermediaries inventory gap risk.

Finally, this paper contributes to the literature on intermediary asset pricing. Haddad and Muir (2021) and He, Kelly, and Manela (2017) show that intermediary constraints can explain variation in returns across many asset classes. Du, Tepper, and Verdelhan (2018) show increased cip deviations around quarter-ends, when banks face tighter capital requirements. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) provide evidence that intermediaries' inventory risk can account for some of the risk premium in options. I document a new source of unhedgeable inventory risk for option intermediaries: Gap risk. The day-night decomposition of option returns suggests that intermediary gap risk explains most of the risk premium in S&P 500 options.

I. Markets and Data

This section outlines the market for S&P 500 options, and briefly discusses equity risk and equity liquidity over day- and night periods. I conclude that differences in fundamental risk cannot explain the concentration of the option risk premium over non-trading periods. Instead, I show that the trade volume in equities and equity futures is substantially reduced at night, which, in combination with intermediaries inventory, provides a potential explanation of the option risk premium. The section briefly states data sources, while details on variable construction are in the respective sections.

S&P 500 Options. This paper studies S&P 500 equity index options (SPX options), i.e., putand 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 \$2tn
a year in 2023 and open interest has grown to about \$250bn. Figure A.4 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 When studying returns, I restrict the sample to SPX options, in order to maintain a similar set of contracts over time. When studying intermediary inventory, I consider both SPX and SPXW options, in order to capture as many intermediary assets as possible with the data. SPX options are liquid across a broad range of strike prices, which occur every \$5. Liquidity is particularly high for out-of-themoney options, which are puts (calls) with strike prices below (above) the current value of the underlying index. SPX options are European, which can only be exercises at expiry. Table A.1 contains further contracts specifications.

S&P 500 Stocks. 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.1 displays cumulative S&P 500 returns over day- and night periods. Table A.1 displays the associated

⁶Specifically, 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.

summary statistics. Day returns are calculated from 09:30 (E.T.) to 16:15, night returns are calculated from 16:15 to 09:30, and both returns are calculated from trade prices. That is, I use the S&P 500 Special-Opening-Quotation as the 09:30 price, and the index close value as the 16:15 price. Over the sample of 1996 to 2023, equity returns average 1.3 basis points during the day, and 1.5 basis points during the night. Day returns are more volatile, with a standard deviation of 99 basis points, compared with 72 basis points for night returns. The lowest day return amounts to -926bps and occurred during the GFC, while the lowest night return reached -1236bps and occurred over a weekend during the covid crash. I conclude that fundamental equity risk is comparable between nights and days and, if anything, is elevated during the day. Consistent with Jones and Shemesh (2018) and Muravyev and Ni (2020), I conclude that differences in fundamental risk cannot explain the day night variation in option returns.

Instead, the concentration of the option risk premium over non-trading periods can be explained by the lower equity liquidity over such periods. S&P 500 futures volumes are low for most parts of the night, relative to intermediaries' liquidity demand. Figure 2 panel (a) shows the dollar trading volume in S&P 500 E-Mini futures for each 30 minute interval of the day. 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. 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 intermediaries.

The reduction of trade volumes over night is even more pronounced in equities than in equity futures. To illustrate stock trading hours, figure 2 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. 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. Trade 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.9 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.

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 intermediary 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.

II. Intermediaries are Exposed to Gap Risk

This section shows that intermediaries' option inventory exposes them to gap risk. Gap risk is the risk of overnight equity price changes. To that end, I document intermediaries' buy- and sell trades in S&P 500 options and cumulate these trades into positions. In call options, intermediaries' buy- and sell volumes are remarkably balanced, while in put options, intermediaries' sell volumes consistently exceed buy volumes. As a result, the intermediary sector has a persistent short position in puts, while the position in calls fluctuates around zero. Due to this inventory, the intermediary sector is exposed to gap risk: If the S&P 500 drops by 10%, intermediaries option inventory looses about \$1.5bn in value. Continuous delta-hedging could prevent such losses, but I estimate that this would require selling about \$15bn worth of stocks, far exceeding the overnight equity trade volumes that are discussed in the previous section. Finally, I show that intermediaries' inventory gamma fails to capture their exposure to gap risk. Instead, I propose shadow gamma as a risk measure.

II.A. Option Trades: Intermediaries 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 intermediary sector. Intermediaries' 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 intermediaries. 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 the option risk premium 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.

Table II shows intermediaries' daily trade volume in S&P 500 options. Intermediaries buy an average of 29.1 million puts a day, while they sell about 30.3 million puts a day. Thus, the intermediary 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 intermediary buyand sell volume in call options is almost identical at 17.5 million contracts a day, leading to intermediary net-buys in call options of approximately zero.

Who buys puts? The literature suggests that intermediaries' 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 to supply such options. As a result, intermediaries hold short put positions in their inventory.

II.B. Option Positions: Intermediaries are Short Puts

I cumulate intermediaries' daily net-buys of S&P 500 options into the intermediary position, via:

$$NetPosition_{t}^{i} = \begin{cases}
\sum_{k=1}^{t} Buys_{k}^{i} - Sells_{k}^{i} & \text{if } t \leq Expiry \\
0 & \text{if } t > Expiry
\end{cases}$$
(1)

where k is a time index from the beginning of my sample to the end of the current day t. I.e., intermediaries' $NetPosition_t^i$ in option i at the end of day t is calculated as the cumulative sum over all past daily intermediary $NetBuys_t^i$. Thus, $NetPosition_t^i$ is the number of contracts of option i that intermediaries are long minus the number of contracts of option i that intermediaries are short. Since options are regularly listed and subsequently expire, this cumulation yields intermediaries' 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. After expiry the intermediary net position drops to zero. Figure A.10 contains a numerical example regarding the estimation of intermediaries' net-position.

Figure A.2 shows the time series of intermediaries' net-position in S&P 500 puts and calls. Intermediaries' position in call options oscillates between +10m contracts and -10m contracts, without any systematic pattern over most of the sample. Intermediaries' zero net-position in calls can explain why call returns are generally insignificant and do not vary between nights and days.

Intermediaries' position in puts is markedly different than their position in calls. In July 2011 intermediaries have a short position in about 20 million puts. This short position gradually increases to around 50 million contracts in early 2018. Subsequently, intermediaries' net-position oscillates at around -10 million contracts. Intermediaries' short put position can explain why put returns are generally negative and are significantly more negative overnight, where hedging frictions are elevated. Intermediaries' put position is negative on the vast majority of days, but experiences a significant shift in early 2018, which I address in the "inventory risk management"

paragraph below.

Table III shows intermediaries' position in S&P 500 put options across option portfolios. I sort options into portfolios by moneyness and days to expiry at market close and report intermediary positions across portfolios. Options are re-assigned at the next market close. Intermediaries 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. In the next section, I show that short-maturity, out-of-the-money puts are the options that are most risky to hold when stocks are illiquid, and they are also the options where most overnight option returns materialize.

II.C. Intermediaries' Inventory Risk Management

Intermediaries sell more puts during times when equity market volatility is relatively low, suggesting that (i) intermediaries actively manage their options inventory and (ii) that equity market risk is a meaningful part of intermediaries inventory risk. The first example of this is the change in intermediaries' short put position around 2018 that is visible in figure A.2. Figure A.7 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.⁷ Thus, intermediaries carry a smaller short put position in their inventory after 2018, but each option exposes them to more risk, due to the higher return volatility of the underlying. Gruenthaler (2022) finds that option intermediaries manage their net-vega exposure in anticipation of spikes in implied volatility. I find evidence that intermediaries manage their equity market risk. The importance of equity market risk for intermediaries' inventory risk is consistent with the interpretation that option risk premia materialize overnight because obstacles to delta-hedging expose intermediaries to equity market risk.

Intermediaries' inventory risk management in the face of equity market risk is visible in their trades. Figure 3 shows a binscatter plot for intermediaries' daily net-buys for 20 bins of lagged realized volatility of the underlying S&P 500 index. The figure shows that intermediaries sell more puts when equity market risk is relatively low. For example, when lagged S&P 500 return volatility is around 5, intermediaries sell an average of 3.4 million put options a day. In contrast,

⁷February 5th 2018 marks the event that traders refer to as "Volmageddon". Augustin, Cheng, and Van den Bergen (2021) describe the event.

when lagged S&P 500 return volatility is around 17, intermediaries sell an average of only 1 million put options a day. The relationship between equity market risk and intermediary 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 by variation in intermediary supply or customer demand. 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 intermediaries are more willing to sell puts when equity markets are calm.

II.D. Intermediaries' Exposure to Gap Risk

Figure A.3 illustrates the main mechanism in this paper: The need to adjust the delta-hedge on a short put position when the price of the underlying changes, and the large risk on such a short put position if one fails to do so. The black line shows the final payoff of a short position in a hypothetical put option with strike 5000, over different possible final prices of the underlying asset. The red curve shows the current value of the short put position, following the Black-Scholes-Merton pricing model, where time to expiry is 7 days and the expected equity return volatility is 30%. The right pink line shows the options' delta at a stock price of 5200, the left pink line shows the options' delta at a stock price of 4800. Assume an initial underlying value of 5200, leading to a Black-Scholes-Merton option price of about \$20 and a delta of about 0.2. Assume now that the underlying price drops continuously to 4800. The Black-Scholes-Merton option price rises to about \$219 and delta rises to about 0.9. The un-hedged return on a short put position in this setting amounts to -995%. An initial delta-hedge would have limited the loss to -658%, but would have required shorting \$884 worth of stocks. A continuously adjusted delta-hedge would have let to a risk-free return at the risk-free rate. However, this would have required continuous selling of \$3484 worth of stocks. This illustrates: Delta-hedging is of first-order importance for option hedging and delta-hedging requires the trading of large amounts of equities for relatively small option positions.

I exploit intermediaries' option positions to estimate their exposure to equity market risk.

Specifically, I estimate the *Profit and Loss (PnL)* of intermediaries' option positions, as:

$$\widehat{PnL}_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times \left[\widehat{P}_{t+1}^i - P_t^i - \Delta_t^i \times (\widehat{SPX}_{t+1} - SPX_t) \right], \tag{2}$$

where \widehat{PnL}_{t+1} is the estimated PnL over period t+1, $NetPosition_t^i$ is intermediaries' net-position in option i at the end of day t as derived above, \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 intermediary 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 likely 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 intermediaries are initially fully delta-hedged, but subsequently do not adjust their option positions or hedges, which captures intermediaries' risk exposure over nights and weekends, when equity market liquidity is low.

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

Figure 4 illustrates intermediaries' exposure to equity price gap risk. The figure shows the estimated profits from intermediaries' 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 \$1.5bn. The losses accrue from price increases on short positions. The estimates do not account for the empirically negative correlation between equity market returns and options' implied volatility. Accounting for this correlation would lead to even higher option prices and larger losses on intermediaries' 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. That is, the estimation does not account for the empirically large option risk premium, and thus does not display the intermediary profits that materialize when absolute equity returns are small.

Figure A.11 illustrates intermediaries' exposure to equity price gap risk, following the method above, but assuming no (initial) delta hedges. The resulting market exposure looks remarkably similar to the estimates above. I conclude that intermediaries' option position is well balanced against small equity price moves. There is little need for delta-hedging with equities as long as the stock returns stay between about -3% and +3%. Only in case of large (negative) equity market returns will intermediaries need to continuously delta hedge in order to avoid losses on their options inventory. These findings are consistent with Hu, Kirilova, and Muravyev (2023), who study Korean data and find only little delta-hedging by option intermediaries. My results suggest this is because intermediaries' option inventory is well balanced against small equity price moves.

II.E. Intermediaries' Liquidity Demand for Delta-Hedge Adjustments

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

$$Interm\widehat{LiqDemand}_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times \left[\widehat{\Delta}_{t+1}^i - \Delta_t^i \right] \times SPX_t,$$
 (3)

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

Intermediaries' liquidity demand for the adjustment of delta-hedges amounts to billions of deltas. Figure 5 shows the estimated intermediary liquidity demand from equation 3 for different

hypothetical returns of the underlying S&P 500 index. The figure shows that, if the underlying index experiences a -10% return, intermediaries would need to sell about \$15bn 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, intermediaries face large constraints on their hedge adjustments over night periods, exposing them to significant inventory risk.

The estimation of intermediaries' liquidity demand likely provides a lower bound. Investor demand for puts likely leads to intermediary 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.

II.F. Intermediaries' Shadow Gamma

I show that intermediaries' gap risk results from options' shadow gamma, not from the common option risk measure gamma. Gamma, measures the curvature in the option value function, and, as such, measures the degree to which delta-hedges become imperfect when the price of the underlying changes. However, over my main sample from 2011 to 2023, the total gamma in intermediaries inventory oscillates around zero and is - if anything - positive. A positive inventory gamma suggests profits from equity price changes, not losses. The reason why gamma fails as a risk measure for intermediaries' option position is that dealers' most pronounced position is a short-position in deep out-of-the-money puts, which experiences large losses in case of an equity market crash, but contributes little to intermediaries inventory gamma, since gamma is close to zero for deep-out-of-the money options. Instead, I find that intermediaries carry large negative shadow gamma. That is, intermediaries' inventory is well balanced against small equity price changes, but if the equity price changes by a large amount, then there will be inventory gamma, equity market risk and inventory losses.

I estimate intermediaries' inventory shadow gamma as:

$$IntermShadowGamma_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times ShadowGamma_t^i,$$
 (4)

where $NetPosition_t^i$ is as defined above and $ShadowGamma_t^i$ measures the gamma of option i at

time t in case of some equity market return, which I estimate on the interval of [-15%, ..., 15%].

Figure 6 displays intermediaries' inventory shadow gamma for different hypothetical returns of the S&P 500. The intermediary gamma at a hypothetical S&P 500 return of 0, shows intermediaries' average current inventory gamma. As indicated above, this value is positive, indicating intermediary profits from S&P 500 returns, and thus failing to capture the intermediary inventory risk over nights and weekends. For both positive and negative S&P 500 returns, the estimated shadow gamma is negative, which captures the expected losses from intermediaries' short put position in case of a large negative S&P 500 return.

My approach to estimating intermediaries' exposure to equity market risk is new to the literature. Since the work of Garleanu, Pedersen, and Poteshman (2009), the literature has focused on intermediaries' net-gamma and net-vega as measures of jump- and volatility-risk respectively. Net-gamma is the sum-product of intermediaries' 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.⁸ Thus, intermediaries' net-gamma approximates the degree to which intermediaries' need to adjust their delta-hedges due to small underlying price changes. Net-gamma measures the local curvature of the value of intermediaries' option portfolio around the current price of the underlying, which approximates intermediaries' risk from jumpsand 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 intermediaries' primary risk exposure, then at-the-money puts should appear most expensive, which is rejected in the data. In contrast, I provide evidence that intermediaries 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. Thus, I explain why out-of-the-money puts are especially risky for intermediaries and consequently why risk premia in such options are especially pronounced.

⁸Gamma 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.

III. Options' Shadow Gamma Predicts Overnight Option Returns

I estimate delta-hedged option returns over days, nights and weekends. Intraday option returns are not significantly different from the risk-free rate. Option returns are more negative over nights than days, and are more negative over weekends than nights. That is, the option risk premium materializes when intermediaries are exposed to gap risk: over nights and weekends. Overnight option returns are more negative in options with more shadow gamma.

III.A. Option Returns: Day vs. Night

I study delta-hedged option returns to prevent my analysis of option returns to be biased by the equity risk premium. It is well known 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.⁹

I calculate delta-hedged option returns as:

$$R_t^i = \frac{P_t^i - P_{t-1}^i - \Delta_{t-1}^i \times (SPX_t - SPX_{t-1})}{P_{t-1}^i},$$
 (5)

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

⁹E.g., Bakshi and Kapadia (2003) and Jones and Shemesh (2018), among many others.

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 intermediaries to quickly adjust their delta-hedges, which exposes them to unhedgeable inventory risk.

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). The dataset aggregates observations 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. Merging with the positions data yields the main sample period of 2011 to 2023.

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 a 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 IV 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%. The associated 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.4 reports bootstrapped standard errors instead of Newey-West t-statistics. Table A.5 regresses the delta-hedged option returns on contemporaneous returns of the underlying equity index and reports summary stats for the resulting alphas. Table A.6 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.7 delta-

¹⁰Average returns are not annualized. Option risk premia are very large relative to most other traded assets.

hedges option returns via the pre-calculated deltas in the CBOE dataset.

Table V separates put returns by weeknights (that is Monday to Friday) and weekends (that is Friday to Monday). Both returns are negative at a highly significant level, but weekend returns are even more negative than weeknight returns. This is consistent with the intermediary gap risk channel, since equity liquidity is especially low over weekends.

Table VI shows overnight S&P 500 put 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 returns 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. Table A.8 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 below. Tables A.9 and A.3 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, I generally restrict the sample to out-of-the-money puts and calls.

III.B. Regress Option Returns on Options' Shadow Gamma

I estimate shadow gamma at the option level. Table VII contains portfolios of puts and calls and shows the estimated gamma of these options after a hypothetical -10% S&P 500 return. Close-to-expiry deep-out-of-the-money puts have a shadow gamma that is about 8 times larger than longer maturity puts and more than 500 times larger than deep-in-the-money puts. Similarly, the shadow gamma of puts is vastly higher than that of calls. Thus, the pattern in shadow gamma across options lines up remarkably well with the pattern in overnight option returns discussed above.

To test the relationship between shadow gamma and option returns, I estimate the following regression specification:

$$R_t^i = \beta_0 \mathbf{1} + \beta_1 Shadow Gamma_{t-1}^i + \beta_2 \times Night_t + \beta_3 Shadow Gamma_{t-1}^i \times Night_t + \epsilon_t^i,$$
 (6)

where $R_{i,t}$ is the return of option i over period t, $ShadowGamma_{t-1}^i$ is the lagged option shadow gamma for a S&P 500 return of (-15%, -10%, -5%), and Night is an indicator for night periods. Option returns are at the option level over days and nights and delta-hedged at the start of the respective period. Returns are in basis points. Shadow gamma is standardized to zero mean and unit variance. Standard errors are clustered at the level of $date \times night$.

Table VIII contains the regression results from Equation 6. The columns contain option shadow gamma for a S&P 500 return of (-15%, -10%, -5%). Across columns, intraday option returns are around 46bps and not significant. Overnight option returns are on average about 245bps below day returns at a high level of significance. Shadow gamma has no predictive power for intraday option returns. The predictive power of shadow gamma for overnight option returns is more negative at a high level of significance. The comparison across columns suggests that gamma is more valuable at more negative equity market returns, i.e. the -15% gamma carries a higher price of risk than the -5% gamma.

IV. Increasing Equity Liquidity Reduces the Option Risk Premium

This section exploits the increase in overnight equity trading around 2006, to study the impact of equity liquidity on the option risk premium. 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 returns are substantially less negative relative to weekend returns after the emergence of overnight equity trading. In this section, I compare option returns from Monday to Friday and Friday to Monday, instead of comaring day returns to night returns, to obtain robust return estimates over the sample of 1996 to 2023.

IV.A. The Growth of Overnight Equity Trading

The institutional details for overnight equity trading developed gradually. In 1991, the New York Stock Exchange introduced its first off-hours trading sessions. 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.

Meaningful overnight equity trade volume emerged some time around 2006. 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 7 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.

The 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 returns. 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 a period of more than 48 hours, where both equity- and equity futures exchanges remain closed, and trade volumes remain unaffected. As a result, if equity liquidity affects the option risk premium, then weeknight option returns should become less negative relative to weekend option returns 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.

Data: Option Returns Intra-Week and Weekend. I obtain daily option data from Option-Metrics, which is the standard dataset for option pricing research. OptionMetrics aggregates option trades at the daily frequency, such that all available observations are at 16:00. 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 observations that violate no-arbitrage bounds.

IV.B. The Change in the Option Risk Premium

In order to study the option risk premium around the emergence of overnight equity trading, I estimate the following regression specification:

$$R_t^i = \beta_1 \operatorname{IntraWeek}_t + \beta_2 \operatorname{Post}_t + \beta_3 \operatorname{IntraWeek}_t \times \operatorname{Post}_t + \epsilon_t^i, \tag{7}$$

where R_t^i is the return of a portfolio of out-of-the-money puts, $IntraWeek_t$ is a dummy for close-to-close returns that are not Friday to Monday, $Post_t$ is a dummy for the period after treatment. I compare intra-week option returns to weekend option returns. Weekend returns are measured from Friday 16:00 to Monday 16:00, intra-week returns comprise of all other daily close-to-close returns. Returns are delta-hedged at the beginning of the respective period. Since the emergence of overnight equity trading cannot be attributed to any specific year, I provide regression estimates with post dummies between 2004 and 2008.

Table IX shows regression estimates of equation 7. Column (1) shows that the average weekend

return before 2004 was -168bps and intra-week returns were higher by 34bps, tough not significantly different. After 2004 the average weekend put return changes by -328bps, while average intra-week put returns changes by 395bps. The crucial coefficient for the diff-in-diff estimation is the interaction of treatment group dummy "IntraWeek" with treatment dummy "Post", which shows relatively less negative option returns over periods where equity trade volume has experienced a relative increase. For robustness, the subsequent columns repeat the estimation for Post dummies in 2005.01 to 2008.01. Across columns, intra-week option returns are significantly less negative relative to weekend returns after the treatment. These results suggest an impact of equity liquidity on the option risk premium, 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.

The increase in the weekend risk-premium 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 the weekend option risk premium after 2008 possibly reflects increased investor attention to risk.

Figure 1 illustrates the change in the option risk premium around the emergence of week-night equity trading. The figure plots the cumulative log returns of out-of-the-money S&P 500 puts over intra-week and weekend periods. The Monday to Friday return is the average over the four returns between Monday close and Friday close. Returns are scaled to the same 10% annualized volatility. Cumulative scaled log returns of out-of-the-money puts are similar over weeks and weekends before 2006, which is indicated with the vertical line. Afterwards, a large and persistent gap emerges between the two cumulative return series.

Table X presents regression estimates for equation 7, but includes the returns of the four out-of-the-money put portfolios and four out-of-the-money call portfolios, with breakpoints as in tables VI and A.3. This estimation allows for the inclusion of a dummy OtmPuts that indicates the portfolio of deep-out-of-the-money close-to-expiry puts. Across columns, the table shows that the change in option returns is elevated in those options where gap risk is concentrated: OtmPuts.

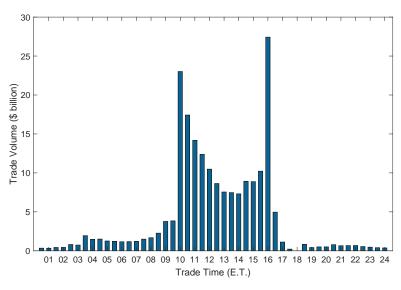
V. Conclusion

This paper shows that intermediary inventory and equity il-liquidity can explain most of the option risk premium. Option returns are negative on average, indicating the presence of an option risk premium. These negative option returns materialize largely over nights and weekends. I find that, due to their options inventory, intermediaries bear inventory gap risk, the risk of equity price changes over nights and weekends, when equity il-liquidity impedes an adjustment of equity market (delta) hedges. Thus, intermediary inventory risk can explain the option risk premium. Intermediaries appear as the marginal seller of options, and, ahead of a night or weekend, they sell options only at high prices, in anticipation of the inventory gap risk that they will have to bear.

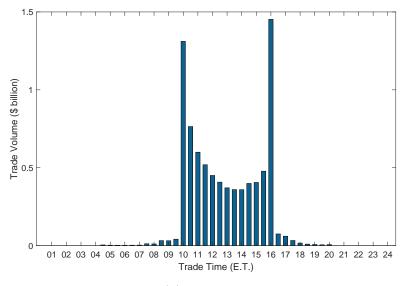
My results have two implications. Regarding the functioning of the options market, my results imply that security market design has a large impact on the option risk premium. Regulators who want to lower hedging costs for option market customers should consider the potentially beneficial impact of around-the-clock market liquidity. Regarding the interpretation of the option risk premium, my results suggest that option returns reflect a combination of customer- and intermediary risk preferences.

VI. Figures

Figure 2: Equity Trade Volume Around the Clock



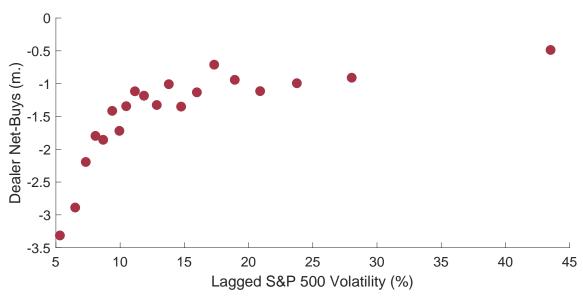
(a) Futures



(b) Apple Inc.

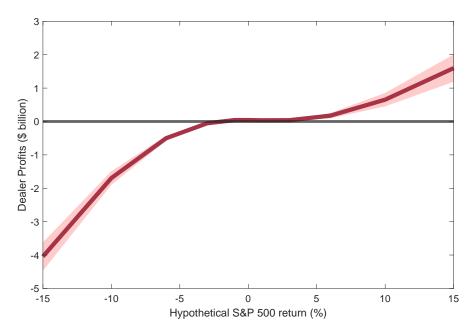
Note: This figure shoes that equity trade volume is relatively small for most parts of the night. The figure shows average trade volumes for each 30-minute interval of the day. Panel (a) contains the most liquid S&P 500 E-mini futures contract, panel (b) contains Apple Inc. stocks, to provide an idea of overnight trade volumes in stocks themselves. The sample period is 2011 to 2023.

Figure 3: Intermediary Put Trading By Lagged Equity Return Volatility



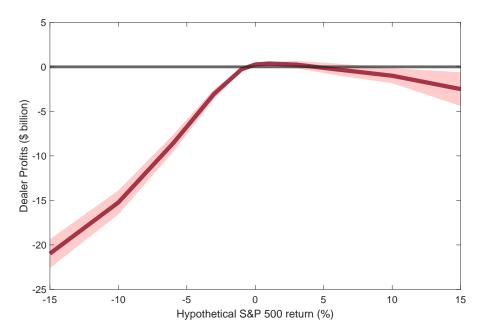
Note: This figure shows that intermediaries sell more puts when equity markets are less volatile. The figure shows dealers' net-buys of puts for different groups of lagged S&P 500 index return volatility. Net-Buys are the daily number of S&P 500 puts bought minus the number of S&P 500 puts sold. Volatility is measured for a rolling window of 10 daily close-to-close returns and is lagged by one day. The sample period is 2011 to 2023.

Figure 4: Expected Dealer Profits for Hypothetical Stock Returns



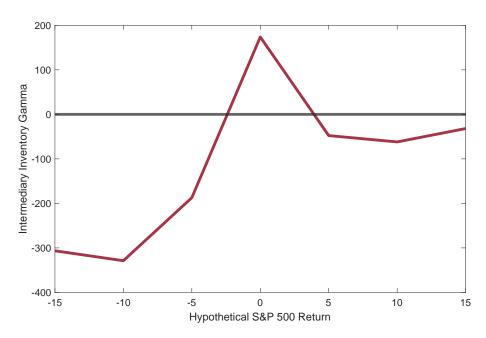
Note: This figure shows that dealers are exposed to overnight equity price gap risk. The figure shows estimated profits of intermediaries' option inventory for different hypothetical overnight returns of the underlying S&P 500 equity index. Option returns are delta-hedged, but hedges are not adjusted. The shaded area shows the 95% confidence interval. The sample period is 2011 to 2023.

Figure 5: Expected Intermediary Liquidity Demand



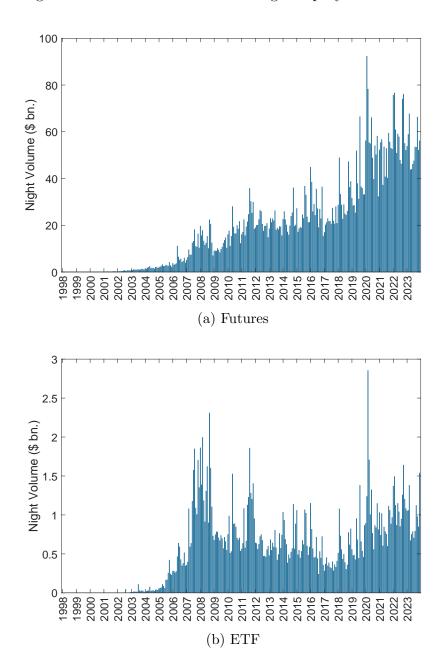
Note: This figure shows dealers' liquidity demand for the adjustment of delta-hedges. Dealers' liquidity demand is estimated for different hypothetical returns of the underlying S&P 500 index via equation 3. The sample period is 2011 to 2023.

Figure 6: Intermediary Gamma and Shadow Gamma



Note: This figure shows dealers' liquidity demand for the adjustment of delta-hedges. Dealers' liquidity demand is estimated for different hypothetical returns of the underlying S&P 500 index via equation 4. The sample period is 2011 to 2023.

Figure 7: The Time Series of Overnight Equity Trade Volume



Note: This figure shows that S&P 500 Night Trade Volume Became Meaningful Around 2006. 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.

VII. Tables

Table I: S&P 500 Equity Returns

	Mean	Std	Min	P1	P50	P99	Max
DayReturn NightReturn	1.3 1.5	$99.4 \\ 71.6$	-926.2 -1,235.7	-275.1 -218.1	4.2 3.9	$279.7 \\ 190.5$	817.8 585.8

Note: This table displays summary statistics for S&P 500 equity returns. Day returns are from 09:30 to 16:15 (E.T.), night returns are from 16:15 to 09:30, and both are calculated from trade prices. Returns are in basis points. P1 indicates the first percentile. The sample period is 1996 to 2023.

Table II: Intermediaries' Option Trade Volume

_	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.

Table III: The Cross-Section of the Intermediary Net-Position in Puts

			Days to Expiry	
		2-70	71-	All
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	-13.54	-3.32	-16.86
$0.25 < \Delta \le 0.50$	Out of the Money	-0.47	-1.47	-1.94
$0.50 < \Delta \le 0.75$	In the Money	0.38	-0.07	0.32
$0.75 < \Delta \le 1.00$	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 II describes the variable construction. Numbers are in millions. The sample period is 2011 to 2023.

Table IV: Option Returns over Nights and Days

	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 returns are significantly more negative over nights than days, while there is no such difference for call option returns. 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.

Table V: Option Returns over Weeknights and Weekends

_	Mean	t-stat	Std	Skew	P10	P50	P90
Weeknight Return (%)	-2.26	-8.49	12.50	10.75	-11.78	-2.17	6.45
Weekend Return (%)	-3.53	-6.38	11.93	2.06	-14.11	-4.46	5.42
Weekend - Weeknight (%)	-1.27	-2.07					

Note: This table shows that put option returns are more negative over weekends, relative to weeknights. Returns are measured from 16:15 to the subsequent 09:45 and are delta-hedged at the beginning of the respective period. Returns are in percent. The sample period is 2011 to 2023.

Table VI: The Cross-Section of Night Put Returns

			Days to Expiry	
		2-70	71-	All
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	-381.7 (-10.9)	-14.4 (-0.8)	-300.6 (-9.9)
$0.25 < \Delta \le 0.50$	Out of the Money	-85.4 (-5.0)	-22.7 (-4.7)	-69.3 (-6.2)
$0.50 < \Delta \le 0.75$	In the Money	-56.8 (-5.0)	-20.1 (-4.1)	-45.1 (-4.6)
$0.75 < \Delta \le 1.00$	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 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.

Table VII: Options' Shadow Gamma, at -10%

			Days to Expiry	
	_	2-70	71-	All
Puts	_			
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	1,207.6	176.0	1,464.7
$0.25 < \Delta \le 0.50$	Out of the Money	132.5	109.9	245.0
$0.50 < \Delta \le 0.75$	In the Money	23.0	21.8	45.4
$0.75 < \Delta \le 1.00$	Deep In the Money	2.2	1.6	3.9
All		1,365.4	310.3	1,762.8
Calls				
$\overline{0.00} \le \Delta \le 0.25$	Deep Out of the Money	5.4	9.6	15.2
$0.25 < \Delta \le 0.50$	Out of the Money	28.4	41.6	70.8
$0.50 < \Delta \le 0.75$	In the Money	73.7	52.8	128.0
$0.75 < \Delta \le 1.00$	Deep In the Money	130.8	17.5	155.8
All	-	252.6	121.6	392.5

Note: The table shows options' shadow gamma. Shadow gamma is the expected option gamma, conditional on a hypothetical return in the underlying asset. This table displays options shadow gamma for an S&P 500 return of -10%. Shadow gamma is multiplied by 1000 for readability. The sample period is 2011 to 2023.

Table VIII: Option Returns on Options' Shadow Gamma

	(-15%)	(-10%)	(-5%)
ShadowGamma	34.5	15.8	-8.4
	(1.50)	(0.70)	(-0.35)
Night	-247.0***	-247.0***	-240.4***
	(-4.10)	(-4.09)	(-3.99)
ShadowGamma x Night	-178.9***	-174.4***	-83.8***
	(-5.82)	(-5.41)	(-2.58)
Constant	46.0 (0.96)	46.5 (0.96)	46.8 (0.97)
Observations	3,225,692	3,225,692	3,225,692
R2-adjusted	0.00	0.00	0.00

Note: The table shows regression estimates of equation 6, where option returns are regressed on options lagged shadow gamma. Columns 1,2,3 contain options shadow gamma for an underlying return of -15%, -10%, and -5% respectively. Option returns are at the option level over days and nights and delta-hedged at the start of the respective period. Returns are in basis points. Shadow gamma is standardized to zero mean and unit variance. Standard errors are clustered at the level of $date \times night$. The sample period is 2011 to 2023.

Table IX: Put Returns around the Emergence of Overnight Equity Trading

	04	05	06	07	08
IntraWeek	33.6	53.0	86.7	116.7**	181.2***
	(0.47)	(0.80)	(1.42)	(2.02)	(3.15)
Post	-327.5***	-297.2***	-264.5***	-249.7***	-214.3***
	(-3.86)	(-3.60)	(-3.27)	(-3.09)	(-2.62)
IntraWeek x Post	395.0*** (4.24)	387.1*** (4.28)	355.8*** (4.00)	326.8*** (3.68)	234.0^{***} (2.59)
Constant	-168.0**	-200.1***	-231.4***	-249.5***	-278.7***
	(-2.55)	(-3.30)	(-4.17)	(-4.80)	(-5.66)
Observations	6,958	6,958	6,958	6,958	6,958
R2-adjusted	0.01	0.01	0.01	0.01	0.01

Note: 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 out-of-the-money S&P 500 puts. Intra-week returns comprise of all daily close-to-close returns, except Friday to Monday. Returns are in basis points and are delta-hedged at the beginning of the respective period. Column 04 (05, etc.) sets the treatment dummy in 2004.01 (2005.01, etc.). The sample period is 1996 to 2023.

Table X: Option Returns around the Emergence of Overnight Equity Trading

	04	05	06	07	08
IntraWeek	34.5	47.8	85.7	100.1*	134.4***
	(0.52)	(0.79)	(1.53)	(1.89)	(2.65)
Post	-166.1**	-137.1*	-84.4	-61.2	-33.7
	(-2.16)	(-1.85)	(-1.17)	(-0.85)	(-0.47)
IntraWeek x Post	181.3** (2.19)	171.2** (2.15)	121.9 (1.57)	105.4 (1.36)	52.4 (0.67)
OtmPuts	-288.3***	-308.2***	-307.3***	-316.1***	-351.9***
	(-2.99)	(-3.39)	(-3.66)	(-4.00)	(-4.71)
IntraWeek x OtmPuts	$39.9 \\ (0.38)$	56.3 (0.57)	61.7 (0.67)	93.0 (1.07)	177.0^{**} (2.05)
Post x OtmPuts	-302.9**	-289.0**	-305.6***	-308.4***	-264.7**
	(-2.53)	(-2.47)	(-2.68)	(-2.74)	(-2.35)
IntraWeek x Post x OtmPuts	454.9*** (3.47)	454.7^{***} (3.55)	470.9*** (3.77)	446.4^{***} (3.60)	325.9*** (2.61)
Constant	-70.1	-95.8*	-134.7***	-151.8***	-169.8***
	(-1.13)	(-1.69)	(-2.59)	(-3.09)	(-3.68)
Observations R2-adjusted	$54,842 \\ 0.00$	$54,842 \\ 0.00$	$54,842 \\ 0.00$	$54,842 \\ 0.00$	54,842 0.00

Note: The table presents regression estimates for a variation 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. This table contains an additional dummy for deep-out-of-the-money short-maturity puts. Option returns are for out-of-the-money option portfolios (4 put portfolios and 4 call portfolios) with breakpoints as in tables VI and A.3. Intra-week returns comprise of all daily close-to-close returns, except Friday to Monday. Returns are in basis points and are delta-hedged at the beginning of the respective period. Column 04 (05, etc.) sets the treatment dummy in 2004.01 (2005.01, etc.). Standard errors are clustered at the daily level. The sample period is 1996 to 2023.

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A.1. Appendix: Figures

1.4
1.2

Day
Night

1.0

Night

0.8

Night

0.4

Night

0.2

-0.2

2000

Figure A.1: Cumulative S&P 500 Equity Returns

Note: This figure plots cumulative returns of the S&P 500 equity index over day and night periods. Day returns are from 09:30 to 16:15 (E.T.), night returns are from 16:15 to 09:30. Returns are from trade prices.

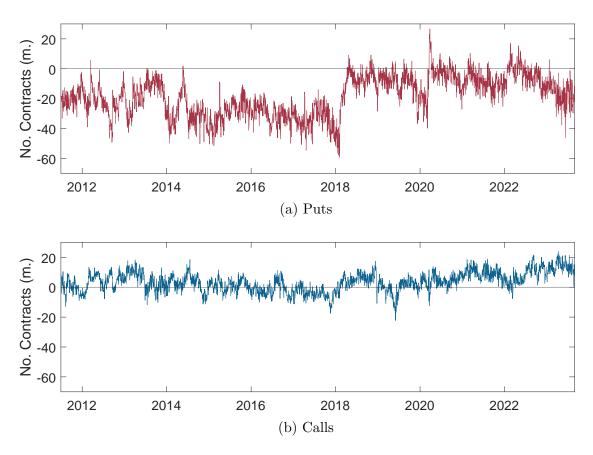
2010

2015

2020

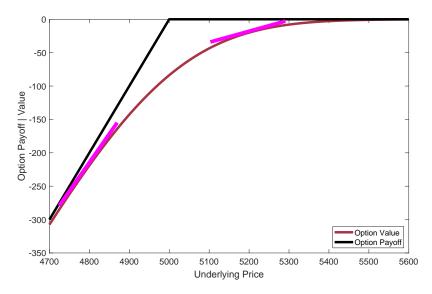
2005

Figure A.2: Intermediaries' Net-Position in Puts and Calls



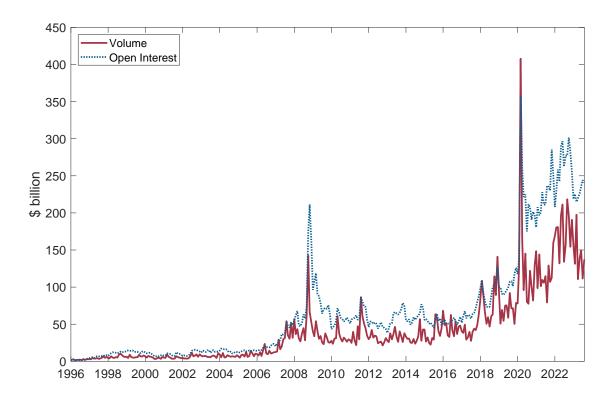
Note: This figure shows that dealers have a persistently negative net-position in S&P 500 put options. Panel (a) shows the daily time-series of dealers' net-position in S&P 500 puts, panel (b) shows calls. Dealers' net-position is the number of contracts that dealers are long minus the number of contracts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

Figure A.3: Illustration: Delta-Hedge Adjustment on a Short Put Position



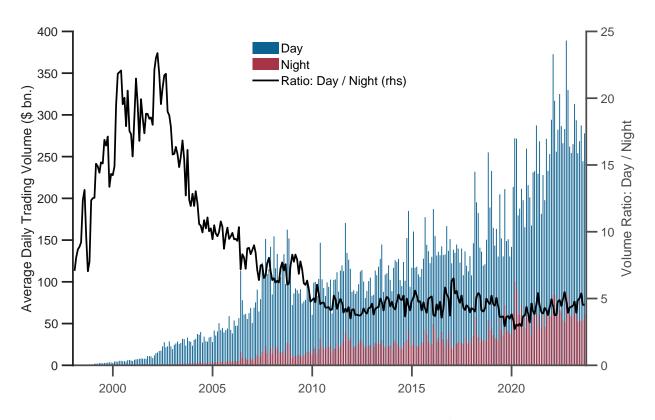
Note: The black line shows the final payoff of a short position in a hypothetical put option, over different possible final prices of the underlying asset. The red curve shows the current value of the short put position, following the Black-Scholes-Merton pricing model, where time to expiry is 7 days and the expected equity return volatility is 30%. The right pink line shows the options' delta (about 0.2) at a stock price of 5200, the left pink line shows the options' delta (about 0.9) at a stock price of 4800.

Figure A.4: S&P 500 Option Market Size



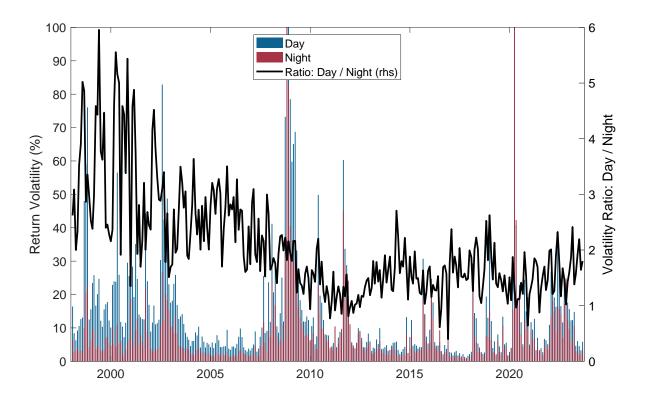
Note: This figure shows that the market for S&P 500 options is large and growing. The upper dotted blue line shows S&P 500 options' average monthly dollar open interest. The lower solid red line shows S&P 500 options' monthly sum of dollar trading volume.

Figure A.5: S&P 500 Futures Trade Volume



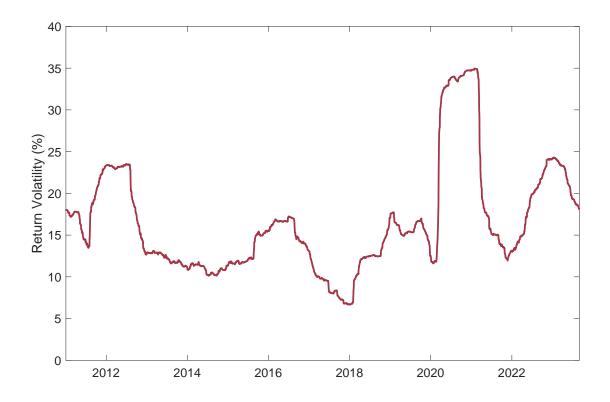
Note: This figure shows the average daily dollar trading volume of the most liquid S&P 500 E-Mini futures contract. The blue (red) line shows monthly average volumes between 0930 (1600) and 1600 (0930). The black line shows the ratio between day and night volumes. The sample period is 2011.1 - 2022.12.

Figure A.6: S&P 500 Return Volatility: Day vs. Night



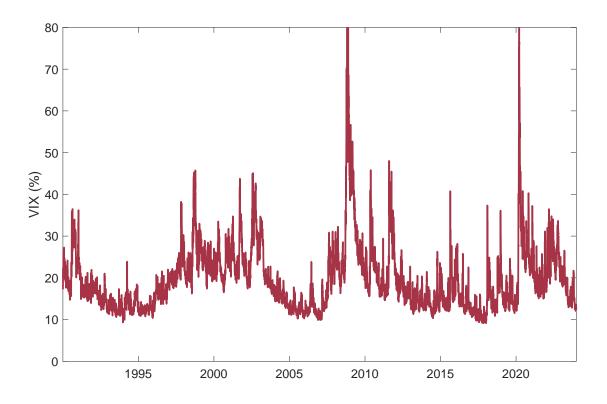
Note: This figure shows that S&P 500 returns are more volatile over day periods than night periods. The figure shows the annualized return volatility of S&P 500 E-Mini futures. Blue (red) bars show the annualized volatility of day (night) returns over the respective month. Day returns are measured between 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.7: S&P 500 Daily Return Volatility, Rolling



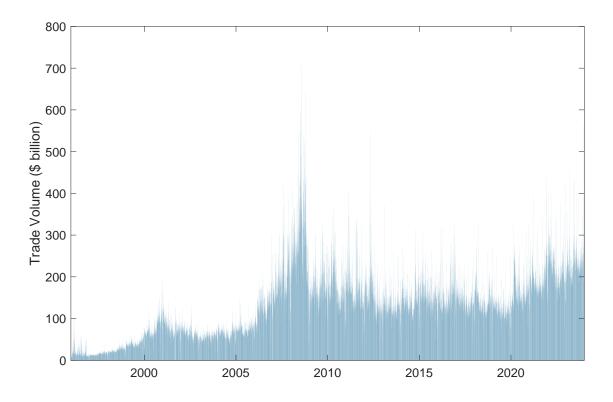
Note: This figure shows the rolling volatility of S&P 500 index returns. Returns are measured close-to-close, i.e. 16:00 to 16:00 (E.T.). Volatility is measured over a rolling 365 day window and is annualized to 252 trade days.

Figure A.8: 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.9: S&P 500 Equity Trade Volume



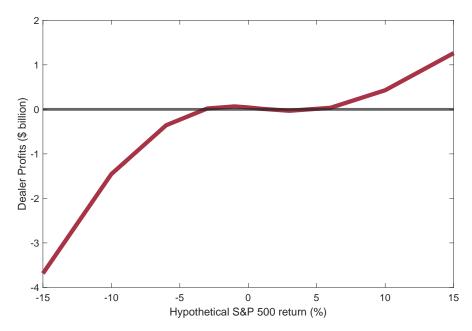
Note: This figure shows the daily trade volume of the S&P 500 constituent stocks.

Figure A.10: Variable Construction: Dealer Position

. I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Weekday	Weekday Date			Put 1				Put 2		Sum Net Position
3.	S	Buys	Sells	Net Buys	Net Position	Buys	Sells	Net Buys	Net Position	S-plane
		(=DB)	(DS)	(=DB-DS)	(=CDNB1)				(=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

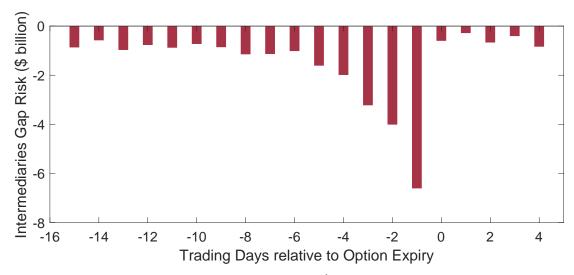
Note: This figure illustrates the construction of the variable *Dealer Net-Position* from the CBOE OpenClose files. The CBOE OpenClose Volume files contain for every day and every option contract the number of contracts that dealers buy (col III) and the number of contracts sell (col IV). *NetBuys* is 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.11: Expected Dealer Profits for Hypothetical Stock Returns: Unhedged



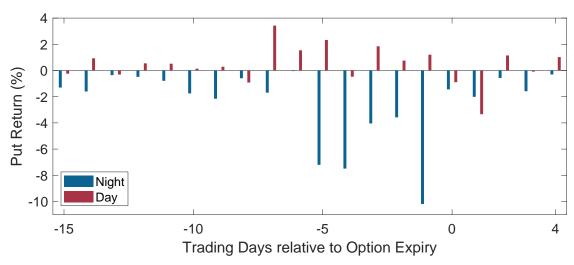
Note: This figure shows the equivalent to figure 4, only that dealer profits are estimated under the assumption that there are no (initial) delta hedges.

Figure A.12: Dealers' Gap Risk: Spiking into 3^{rd} Friday Option Expiry



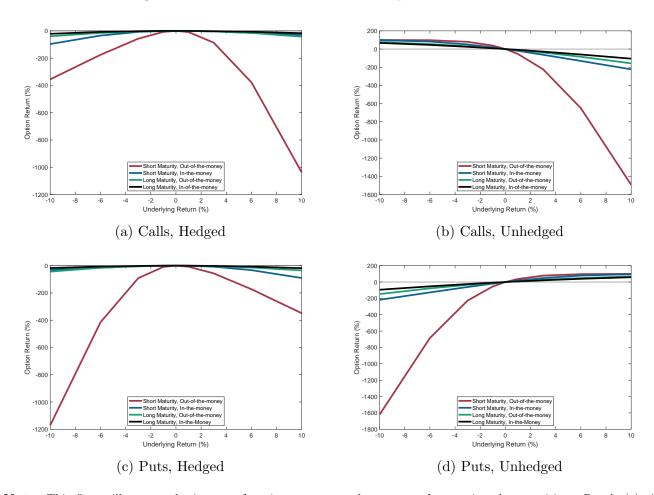
Note: This figure shows that dealers' gap risk spikes into the 3^{rd} Friday option expiry. The figure plots dealers' equity market gap risk as estimated in section II relative to each months' 3^{rd} Friday, where the standard SPX options regularly expire. Day 0 marks the 3^{rd} Friday, where risk is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

Figure A.13: 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.14: Illustration: Returns of Option Short Positions



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).

A.2. Appendix: Tables

Table A.1: 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.2: Intermediaries' Gap Risk: Summary Stats

	Mean	Std	Skew	P5	P50	P95
Intermediary Gap Risk (\$ bn)	1.5	5.2	3.4	-3.7	0.9	8.4

Note: This table shows summary statistics for option dealers' inventory risk exposure to overnight equity price gaps as estimated in section II. That is, the table shows the estimated dealer Profit-and-Loss from a -10% return in the underlying S&P 500. Inventory risk is in billions of dollars. The sample period is 2011 to 2023.

Table A.3: The Cross-Section of Night Call Returns

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

Note: The table shows average S&P 500 call 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.

Table A.4: 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.5: 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.6: Option Returns 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 IV 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.7: Option Returns 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 IV 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.8: The Cross-Section of Day Put Returns

			Days to Expiry		
		2-70	71-	All	
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	58.0 (1.6)	-0.2 (-0.0)	41.7 (1.4)	
$0.25 < \Delta \le 0.50$	Out of the Money	-1.2 (-0.1)	-1.0 (-0.3)	-3.9 (-0.3)	
$0.50 < \Delta \le 0.75$	In the Money	$\frac{1.8}{(0.2)}$	-2.0 (-0.2)	$0.9 \\ (0.1)$	
$0.75 < \Delta \le 1.00$	Deep In the Money	4.2 (0.3)	22.9 (1.3)	$4.6 \\ (0.3)$	
All		45.0 (1.6)	-0.7 (-0.1)	32.9 (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.9: The Cross-Section of Day Call Returns

			Days to Expiry	
		2-70	71-	All
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	-0.5 (-0.0)	17.8 (0.6)	5.0 (0.1)
$0.25 < \Delta \le 0.50$	Out of the Money	$4.0 \\ (0.3)$	8.8 (0.0)	$2.5 \\ (0.2)$
$0.50 < \Delta \le 0.75$	In the Money	$\frac{2.6}{(0.3)}$	4.9 (1.1)	$\frac{2.8}{(0.3)}$
$0.75 < \Delta \le 1.00$	Deep In the Money	$6.0 \\ (0.9)$	-5.8 (-0.5)	$3.0 \\ (0.7)$
All		39.2 (0.8)	24.7 (1.4)	35.6 (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.10: The Cross-Section of Dealers' Call Position

		Days to Expiry		
		2-70	71-	All
$0.00 \le \Delta \le 0.25$	Deep Out of the Money	-0.84	-0.50	-1.33
$0.25 < \Delta \le 0.50$	Out of the Money	1.55	0.87	2.42
$0.50 < \Delta \le 0.75$	In the Money	1.40	0.47	1.87
$0.75 < \Delta \le 1.00$	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 II describes the variable construction. Numbers are in millions. The sample period is 2011 to 2023.