Internet Appendix for

"Why Do Option Returns Change Sign from Day to Night?"

This Appendix reports several additional results for "Why Do Option Returns Change Sign from Day to Night?" Specifically, it includes the following: (a) several figures and tables that complement the main results; (b) results from computing option returns using trade prices and for (c) straddle and unhedged option returns and (d) day-night volatility seasonality; (e) details of the Black-Scholes-Merton (BSM) and Heston models with day-night volatility seasonality; and (f) the overnight trading strategy net of trading costs.

A.1. Properties of Day Night Option Returns

Several tests enhance understanding of how each year, especially during the financial crisis, contributes to intraday returns. First, each year's intraday return, including 2008, is not statistically different from the average returns excluding the given year. Thus, individually, none of the years is special in this statistical sense. Next, after excluding the crisis, average intraday returns are still positive but not statistically significant (t-statistic = 1.7). Even zero return would be puzzling though. We also study how much of this result is owing to noise in prices. The S&P500 index, albeit important, is merely a single security, so averaging across multiple securities reduces noise in option returns (e.g., due to large bid-ask spreads). This is why we also study average option returns of the three most liquid ETFs: S&P 500 (SPY), NASDAQ 100 (QQQ), and Russell 2000 (IWM). Besides SPX, these three have the most actively traded options in OPRA data. Their total option volume is still lower than S&P500 index options (Johnson, et al. (2016)), but their option bid-ask spreads are less than half the size of SPX's. Obviously, SPY and SPX returns are extremely correlated. Panel B of Table A.2 shows that average option intraday returns over these three ETFs are positive in eight out of ten years (with the exception of -0.17% in 2004 and -0.05% in 2012). Similarly, Panel A studies equity option returns by year. Intraday returns are positive in all but three years: -0.16% in 2009, -0.08% in 2010, and -0.11% in 2012. For both major ETFs and equity options, their 2008 returns are expectedly more positive than in other years, but average intraday returns excluding the crisis remain positive and significant. Averaging across multiple contracts with lower option bid-ask spread indeed reduces noise in option returns.

We also show the day-night option returns asymmetry cannot be explained by S&P 500 index returns and VIX futures returns. Table A.6 estimates a regression of S&P index option returns on VIX futures returns and S&P index returns separately for day and night periods. First, delta-hedging works reasonably well, as the coefficient for index returns is zero intraday and relatively small overnight. Second, intraday returns for options and VIX futures are highly correlated with t-statistic of 17. However, night returns are much less correlated, as the coefficient is lower than for intraday (0.66 versus 0.92) with t-statistic of 5.6. Perhaps the options and volatility futures markets are less integrated during the night. Importantly, volatility and market risk factors explain only a small portion of the day-night effect. Indeed, the intercept, which corresponds to alpha/abnormal returns, is 0.24% for intraday, which is close to 0.28% average intraday return. Night return decreases slightly from -1.08% to -0.89% after controlling for market and volatility factors.

To explore how S&P 500 option returns depend on market conditions, we estimate time-series regressions of day and night returns and their difference on popular predictors, including day-night volatility ratio, absolute stock return as proxy for realized volatility, option bid-ask spread, implied volatility, volatility skew, variance risk-premium, implied volatility spread, and option order imbalances computed from open-close and intraday data. Table A.12 shows that none of the variables significantly predicts the day-night return difference. The IV spread and intraday order imbalance negatively predict next-day overnight returns, while open-close imbalances positively predict next-day intraday return only. Out of nine predictors, only few are marginally statistically significant. Perhaps we do not have enough statistical power to study conditional properties of S&P day-night option returns. This is why our main tests use a panel of equity option returns.

We also sort trading days into portfolios based on market volatility, tail risk, option liquidity, interest rates, and investor sentiment. Panel A of Table A.11 shows that market conditions produce little variation in overnight returns. Night returns are slightly more negative when VIX is high, and interest rates and investor sentiment are low. Intraday returns, conversely, are positive when volatility is high or option liquidity is low. Option intraday returns are also increasing in the AAII investor sentiment, which is based on a survey of how bullish investors are about the stock market, but are decreasing in the Baker and Wurgler (2006) sentiment. Interestingly, the BW sentiment is the only variable that produces significant high-low spread for both night and day returns (-0.62% and -0.54%). Next, we use two popular tail risk measures proposed by Bogou and Jiang (KJ, 2014) and Du and Kapadia (DK, 2012) to explore whether rare disasters or tail risk can explain the day-night effect. Panel B of Table A.11 shows that systematic tail risk produces little variation in either day or night option returns.

Finally, we compare day and night return distributions for the underlying in Table A.1. S&P 500 index returns are close to zero: 0.008% overnight and -0.004% intraday. That is, the difference is only one basis point and is not statistically significant.

A.2. Option Returns Using Trade Prices

In this section, we show that our main result is robust to computing option returns using trade prices instead of the quote midpoints. Computing returns with the quote midpoints is a de facto standard and for good reason. Besides being supported by many microstructure models, the quote midpoint has advantageous empirical properties: it is intuitive, observed at every instance, and not affected by the bid-ask spread bounce. In some markets, there is concern about whether the bid and ask prices are tradable; but in the options market, the majority of trades are executed within the bid-ask spread. For equity options, most trades are executed at either the bid or ask.

The advantage of using trade prices is that these are actual transactions, and thus there is less uncertainty about tradability. Unfortunately, trade prices are obviously only observed at the time of a trade. Thus, to estimate intraday option returns with trade prices, our sample is perforce limited to option contracts that traded near both the open and close on a given day. A similar criterion is used for overnight returns (trade around close of the previous day and open of the current day). This requirement greatly reduces the sample size, as many options trade infrequently. Also, trade prices are noisy, due to the bid-ask spread bounce, as buyer-initiated (seller) trades are typically executed above (below) the fair value.

We first compare average trade prices with the quote midpoints, and then compare day and night option returns for two approaches. Panel A of Table A.8 reports the dollar and relative differences between option trade prices and midpoints. For each trade, we compute the difference between the trade price and the pre-trade quote midpoint. We further normalize it by the quote midpoint to compute the relative difference. We do not account for the trade direction (as in the effective bid-ask spread) because we study the bias between two prices and not transaction costs.

Both differences are slightly positive, meaning that trade prices are systematically higher than quote midpoints. This is to be expected because buyer-initiated trades outnumber sells for index options. The dollar difference is 0.63 cents on average and ranges between 0.24 cents in the morning to 0.99 cents in the afternoon (average option price is about seven dollars). Similarly, the relative difference is 0.09% and ranges from 0.07% to 0.12%. Almost by construction, the price difference tracks closely the patterns in order imbalance discussed in Section 4.2 and shown in

Table 6. Order imbalance is positive for index options, particularly in the afternoon. Simple ad hoc calculations show that the price difference is mostly driven by positive order imbalance. Multiplying a 3% order imbalance from Table 6 by a 3% typical effective bid-ask half-spread produces a 0.09% expected bias, which matches the price difference in Table A.8. Also, note the 0.05% difference in prices between morning and afternoon (0.12% minus 0.07%) is small compared to intraday option returns (0.3%). Overall, the effect of buys and sells cancel each other, and the average trade price is relatively close to the quote midpoint.

Of course, the most important test here is to compare not just prices but option returns. As both open and close trade-based prices are slightly higher than option quote midpoints, this small positive bias cancels out and produces similar option returns as returns based on the quote midpoints. We compute option returns using trades the same way as from the quotes except we only delta hedge once intraday. The reason is that the sample of options that trade at every intraday subperiod cut-off is small, and the benefits of frequent delta-hedging are small.

Panel B of Table A.8 shows a 0.44% average intraday return and a -2.26% night return with t-statistics of 2.8 and -17.8. The return magnitudes are larger than the baseline's (quote midpoint) case (0.29% and -1.04%) because the subsample of traded options overweighs short-term options, as they are traded more frequently. We find similar magnitudes for both call and put options. As for the quote midpoint case, returns are more extreme for out-of-the money options because of their higher leverage. Interestingly, overnight returns are close to zero for deep-in-the money options, perhaps because these options rarely trade. Long-term and ITM options trade infrequently, while OTM short-term options are the most liquid.

Overall, our main result is robust when using option trade prices instead of the quote midpoints for computing option returns. However, both approaches to computing option returns make an implicit assumption that the quote midpoint (trade price) is perhaps noisy but represents an unbiased estimate of the option fair value. The fair value can potentially be anywhere between the bid and ask price, which could be far apart because of the large option bid-ask spreads. Our results in this section and other robustness tests significantly reduce, but not completely eliminate, this concern.

A.3. Straddle and Unhedged Option Returns

Our main return measure, the delta hedged option return, relies on the ability to hedge a call/put by trading in the underlying. This can raise several potential concerns. First, the timestamps could be desynchronized across the two markets, thus leading to put-call parity violations and other microstructure effects. Luckily, our data are synchronized up to a few milliseconds, as the data provider aggregates from both markets simultaneously. Second, trading in the underlying requires posting margin that may not be properly accounted in option return calculations. Finally, as the portfolio consists of options and the underlying, it could be the case that the underlying part rather than option position drives our return results.

In this section, we study two option return measures that do not require hedging in the underlying to elevate these concerns. Raw returns require no delta-hedging, while straddle returns are hedged by combining calls with corresponding puts. Raw returns are equivalent to delta hedged returns with option delta set to zero; as such, they can be computed similar to delta hedged returns. Panel B of Table A.7 reports average raw option returns. The results appear favorable. Day and night option returns are 0.22% and -0.93% per day respectively with t-statistics of 2.3 and -12.1. Taking an average across calls (positive delta) and puts (negative delta) to compute returns on a given day provides implicit delta-hedging (the residual delta is small). As a result, average raw returns have similar magnitudes to the delta hedged returns in Table 1. Then we compute raw returns separately for calls and puts; intraday returns are similar (0.3%), but calls have almost two times less negative returns overnight (-0.6% vs. -1.1%). This pattern is consistent with the equity risk premium being small intraday and large overnight (calls have a positive delta and thus benefit from positive stock returns).

We form a straddle portfolio by combining a call with as many corresponding puts (with the same strike and expiration) to make it delta-neutral. A typical straddle portfolio includes one call and one put (on average). We then compute straddle returns the same way as raw returns for a delta hedged portfolio (i.e., no delta-hedging is done except for combining calls with puts). As reported in Panel A of Table A.7, straddle returns are similar to delta hedged returns in Table 1. Day- and night-option returns are 0.18% and -0.85% per day, respectively, with t-statistics of 2.5 and -17.7. The day-night return asymmetry is observed for all moneyness categories. Finally, forming a straddle portfolio our way is not critical for our results, because as for the raw returns there is implicit delta-hedging from averaging over call and put returns.

Overall, results for raw and straddle returns together with other robustness tests in the paper suggest that our main results are robust to delta-hedging.

A.4. Day and Night Volatility

In this section, we explore the day-night volatility seasonality, the main ingredient of the volatility bias. We explore the seasonality for stocks and S&P 500 index. Although it is well-known that volatility is higher intraday, surprisingly little is known about how much higher it is. Using five stocks between 1974 and 1977, Oldfield and Rogalski (1980) find the day-night volatility ratio of 2. For 50 stocks from the Tokyo exchange, Amihud and Mendelson (1991) show that volatility is higher in trading compared to non-trading periods. Converting their estimates of day and night return variances produces a day-night volatility ratio of 1.5. Stoll and Whaley (1990) find a volatility ratio of 2.3 for NYSE stocks during 1982 through 1986. These estimates are broadly consistent with what we find in our sample. Surprisingly, more recent references are seemingly not extant.

To compute the day-night volatility ratio, we first compute night (close-to-open) and day (open-to-close) volatilities as standard volatility but with close-to-open and open-to-close returns (i.e., night volatility is an average of a square root of the sum of squared close-to-open returns over the previous 60 days). To make day and night volatilities comparable on a per-hour basis, we convert day and night volatilities to the same (per-hour) time length using a conversion ratio of 1.64 ($=\sqrt{17.5/6.5}$) as night and day periods are 17.5 and 6.5 hours, respectively. We then compute a simple ratio of the intraday and overnight volatilities.

Figure 3 shows day and night volatilities and their ratio for S&P500 index over our sample period. Both volatilities expectedly spike during the financial crisis and remain low otherwise. However, the volatility ratio is surprisingly stable even during the crisis. The ratio slowly decreases from about 3.5 in 2004 to about two in 2013. Most of the decease occurred during the late 2007 to 2009 period, then stock liquidity improved substantially owing to regulatory changes. Interestingly, the decreasing trend in total volatility that received so much public attention recently is due to the decline in intraday, rather than overnight, volatility. We also explore volatility ratio trends for individual stocks. Figure A.2 shows how distribution of the volatility ratio across stocks (quantiles and the mean) evolved over the sample period. Average volatility ratio declined from 3.4 to 2.8, much less than for the index. The distribution is fairly symmetric, with the mean and median tracking each other closely. The top and bottom deciles have a volatility ratio of 4.5 and 1.6, respectively, and are consistent over time. The fact that the day-night volatility ratio does change over time is important. The volatility literature typically estimates realized volatility from intraday data and then annualizes it using an ad hoc day-night volatility ratio. We argue that the day-night volatility ratio should be estimated carefully, otherwise such volatility estimates may be substantially biased.

Overall, the volatility ratio fluctuates in a relatively narrow range (e.g., from 1.5 to 3.5 for S&P index). We use this range to simulate day and night option returns for a grid of plausible volatility ratio values. We leave for future research to enhance understanding of the economics behind the trends in the volatility ratio.

A.5. BSM Model with Volatility Seasonality

In this section, we explain the details of how we add the day-night volatility seasonality and the volatility bias to the standard Black-Scholes-Merton model. We first explain the basic procedure for the BSM model with the volatility seasonality. The underlying price, S_t, follows a geometric Brownian motion with deterministic time-varying volatility to introduce the day-night volatility seasonality. In particular,

$$\frac{dS_t}{S_t} = \mu dt + \sigma_t dB_t, \qquad \text{(A.1)}$$

where B_t is a simple Brownian motion, and σ_t is the annualized *instantaneous* volatility for the underlying. To introduce the volatility seasonality, we set *instantaneous* volatility $\sigma_t = \sigma_{day}$ for intraday periods, and $\sigma_t = \sigma_{night}$ for overnight periods, with $\sigma_{day} > \sigma_{night}$. Obviously, this is a minor adjustment to the classic BSM model, and option prices can be easily solved for. The European call and put option prices for the no dividend case are:

$$Call_t = S_t N(d_1) - Ke^{-r_f(T-t)}N(d_2), \qquad \text{(A.2)}$$

$$Put_t = Ke^{-r_f(T-t)}N(-d_2) - S_t N(-d_1),$$

where

$$d_1 = \frac{ln\left(\frac{S_t}{K}\right) + r_f(T-t) + \frac{1}{2}[\sigma_{day}^2(T-t)_{day} + \sigma_{night}^2(T-t)_{night}]}{\sqrt{\sigma_{day}^2(T-t)_{day} + \sigma_{night}^2(T-t)_{night}}},$$

$$and, d_2 = d_1 - \sqrt{\sigma_{day}^2(T-t)_{day} + \sigma_{night}^2(T-t)_{night}},$$

and $N(\cdot)$ is the cumulative function of standard Gaussian distribution. $(T-t)_{day}$ is a sum of the day periods over $T-t$, in years. Similarly, $(T-t)_{night}$ is a sum of the night periods. These simple formulas collapse to the standard BSM prices if $\sigma_{day} = \sigma_{night} = \sigma$.

We choose model parameters to match key return moments of the S&P 500 index and its options during our sample period 2004 to 2013. In particular, we assume an expected return of $\mu = 5.08\%$, volatility $\sigma = 14.88\%$, risk-free rate $r_f = 1.52\%$, and implied volatility $\sigma^{IV} = 21\%$. The implied volatility σ^{IV} is set higher than the actual volatility σ to produce the -0.7% daily delta hedged option return observed in the data. Higher σ^{IV} relative to σ is a common way to introduce the variance risk premium in the BSM model. We initially set the day-night volatility ratio $\lambda = 2.5$, but also consider other plausible values. The day-night ratio is simply the ratio of two instantaneous volatilities $\lambda = \frac{\sigma_{day}}{\sigma_{night}}$. Panel A of Table A.15 summarizes parameter values.

We can compute average daily variance using time-weighted day and night variances:

$$\sigma^2 = \frac{17.5}{24}\sigma_{night}^2 + \frac{6.5}{24}\sigma_{day}^2 \tag{A.3}$$

where night and day periods are $T_{night} = 17.5$ and $T_{day} = 6.5$ hours respectively, and σ_{day} and σ_{night} are *instantaneous* (per hour) day and night volatilities. We set volatility σ to match historical data and choosing the day-night volatility ratio (e.g., $\lambda = 2.5$), we can then compute σ_{day} and σ_{night}. I.e., $\sigma_{day}\ (\sigma, \lambda)$ and $\sigma_{night}\ (\sigma, \lambda)$.

After model parameters are set to match historical data, we simulate the model to compute day and night option returns. E.g., for overnight returns, we first compute the option price at the close with Eq. (A.2). We then simulate close-to-open returns for the underlying using Eq. (A.1), and compute open price for the same option using Eq. (A.2), which takes into account the new underlying price. We then compute the overnight option return from close and open prices for the option and the underlying using Eq. (1) and (2). We similarly compute intraday returns from simulated open and close prices. We simulate the model using a 20-year period and a 365-day year. The first 10% of the sample is treated as burn-in period and, therefore, is discarded. We then average option returns over all the simulations.

How do we add the volatility bias? Eq. (A.2) assumes that options are priced using the correct day-night volatility ratio λ. The volatility bias argues that options are priced using incorrect volatility ratio $\lambda^{IV} \neq \lambda$. Thus, the bias can be easily included in the model by simply computing option prices using $\sigma_{day}\,(\sigma, \lambda^{IV})$ and $\sigma_{night}\,(\sigma, \lambda^{IV})$ but using the correct ratio λ to simulate the underlying price.

A.6. Heston Model with Volatility Seasonality

The Heston (1983) stochastic volatility model is a common way to introduce the negative variance risk premium. We add the volatility seasonality to the standard Heston framework. In particular, the underlying price follows,

$$\frac{dS_t}{S_t} = \mu dt + \sqrt{V_t} dB_t^1, \tag{A.4}$$

where B_t^1 is a Brownian motion with no drift. V_t is the *instantaneous* stochastic variance. The stochastic volatility follows square-root mean-reverting process,

$$dV_t = \kappa(\theta - V_t)dt + \eta\sqrt{V_t} dB_t^2, \tag{A.5}$$

where κ is the mean-reverting speed, θ is the long-run variance, η is the volatility of volatility. B_t^2 is a standard Brownian motion with no drift. In addition, $dB_t^1 \cdot dB_t^2 = \rho dt$, where $\rho < 0$ to reflect the leverage effect.

In a risk-neutral world, the Heston model can be written as:

$$\frac{dS_t}{S_t} = rdt + \sqrt{V_t} dB_t^{1,Q}, and,$$

$$dV_t = [\kappa(\theta - V_t) - \gamma V_t]dt + \eta \sqrt{V_t} dB_t^{2,Q}, \tag{A.6}$$

where γ is the price of volatility risk, and $\gamma < 0$ indicates a negative variance risk premium. $B_t^{1,Q}$ and $B_t^{2,Q}$ are Brownian motions under risk-neutral measure, where $dB_t^{1,Q} \cdot dB_t^{2,Q} = \rho dt$ and $\rho < 0$. We set model parameters to match historical data and Broadie et al. (2007). We summarize them in Table A.15.

To introduce volatility seasonality, we make the following adjustments: in particular, we treat V_t as a hidden conditional variance process with adjustments to adapt to day and night variance. The seasonality-adjusted variance, SV_t, is therefore,

$$SV_t = \begin{cases} V_t^{day} = \nu^{day} V_t \\ V_t^{night} = \nu^{night} V_t \end{cases}, \tag{A.7}$$

i.e., the implementation is very similar to the BSM model. We scale instantaneous variance up during day and down during night.

$$V_t = \frac{17.25}{24} V_t^{night} + \frac{6.75}{24} V_t^{day} \tag{A.8}$$

$$\lambda = \sqrt{\frac{V_t^{day}}{V_t^{night}}} = \sqrt{\frac{\nu^{day}}{\nu^{night}}}$$

As with the BSM model, we set volatility V to match historical data and choosing the day-night volatility ratio (e.g., $\lambda = 2.5$), we can then compute ν^{day} and ν^{night}.

We incorporate volatility bias and simulate the model to compute option returns in the same way as for the BSM model in the previous section. To compute overnight option returns, we first compute the closing option price using "biased" volatility ratio $\nu_{day}\,(V, \lambda^{IV})$ and $\nu_{night}\,(V, \lambda^{IV})$ and then simulate the overnight change in the underlying using Eq. (A.4) with the correct volatility ratio λ, and then compute open option price under λ^{IV} using the new underlying price (time-to-maturity, etc.). We then compute overnight option return from close and open prices for option and the underlying using Eq. (1) and (2).

A.7. Trading Strategy

Practitioners may wonder whether the day-night bias can be turned into a trading strategy by profiting from large overnight returns. The short answer is yes, but only for certain options and only for investors who are very careful about their trade execution (e.g., hedge funds specializing in both trading options and trade execution). The costs for average investors are too high; however, they can still benefit from the day-night effect and reduce costs and risks by executing their option sales in the afternoon instead of the morning. Importantly, marginal investors who have low execution costs, not average investors, are responsible for arbitraging away such "good deals."

At first glance, the option trading costs are excessive. E.g., the effective bid-ask spread for S&P 500 index options is about 6% in our sample. Hardly any option trading strategy is profitable after accounting for these spreads. Do most investors pay such large spreads? No! Muravyev and Pearson (2016, MP henceforth) show that most investors time their trades and pay lower spreads. Trade timers pay as much as one fourth of the effective bid-ask spread when taking liquidity. Of course, investors can also reduce costs by providing liquidity with limit orders. We focus on the bid-ask spread as it is typically much larger than other option costs, such as hedging costs in the underlying, brokerage/exchange commissions, margin/funding costs, execution uncertainty, and price impact; however, these costs should be accounted for in a more thorough analysis.

For the trading strategy, we focus on options on SPDR S&P 500 ETF (ticker SPY), the world's most liquid ETF, that are a close substitute for S&P index options but incur much lower transaction costs. Next, we compute trading cost measures introduced by MP (2016). That is, using the option trade data, we compute the effective bid-ask spread adjusted for the fact that many investors time their trades to reduce transaction costs. Following MP (2016), each trade is assigned the likelihood of being initiated by an execution timing algorithm, which allows us to compute trading costs for two investor types: execution algorithms ("algos," those concerned with trading costs and time their trades accordingly) and everybody else ("non-algos," which represents an average investor).

In Table A.20, we compare overnight returns and trading costs for SPY options. Results are reported for two subperiods: before and after the Penny Pilot reform that reduced the tick size for SPY options to one penny on September 28, 2007. SPY options were launched in January 2005. An average night return for SPY options is -0.64% (an intraday return is 0.18%), and is identical before and after the Penny Pilot. However, trading costs decreased substantially after the tick size reduction. The costs for non-algos, which are equal to the conventional effective bid-ask spread, decreased from 3.9% to 1.2%. Algo-traders' costs declined from 0.66% to 0.05%. Thus, a hypothetical trading strategy that sells SPY options overnight and incurs transaction costs typical for an algo-trader breaks even in the pre-Pilot period (-0.01% = 0.65% - 0.66%) and is highly profitable in the post-Pilot period (0.6% per day), as the profits do not change while the costs decrease noticeably. We use the transaction costs for algo-traders because they are the marginal investors in this high-cost market. Other investors' costs are too high to profit from this strategy.

Overall, option trading costs fell after the Penny Pilot, thus making the overnight strategy potentially profitable for algo-traders, but only for them. Of course, the debate about after-cost profitability of the overnight strategy does not answer a more fundamental question about why this effect exists in the first place.

Figure A.1 Intraday option returns and delta-hedging frequency.

We report how average intraday returns for S&P500 index options depend on the frequency of delta-hedging from one time per day to five times, which is our baseline case. We also report 95% confidence intervals.

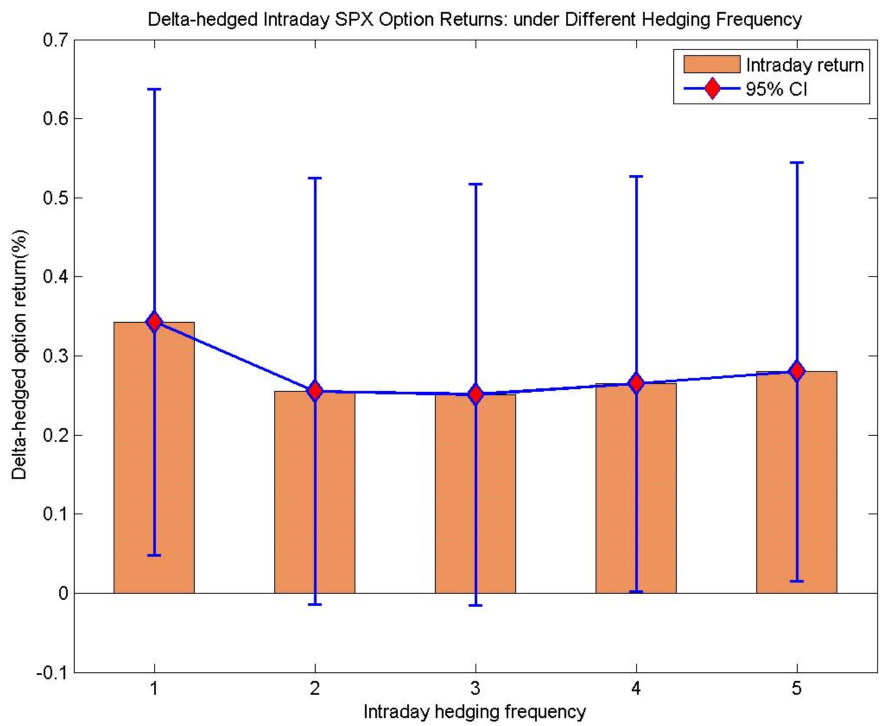

Figure A.2 Day and night volatility for individual stocks

We first compute the day-night volatility ratio for each stock and then plot the distribution quantiles on each month. We report 10%, 25%, 50%, 75%, and 90% quantiles and the mean, which is close to the median. Overnight (intraday) volatility is computed as an average of the square root of the sum of squared close-to-open (open-to-close) returns over the previous 60 days. Both volatilities are then scaled to per-hour basis to make them comparable before computing their simple ratio.

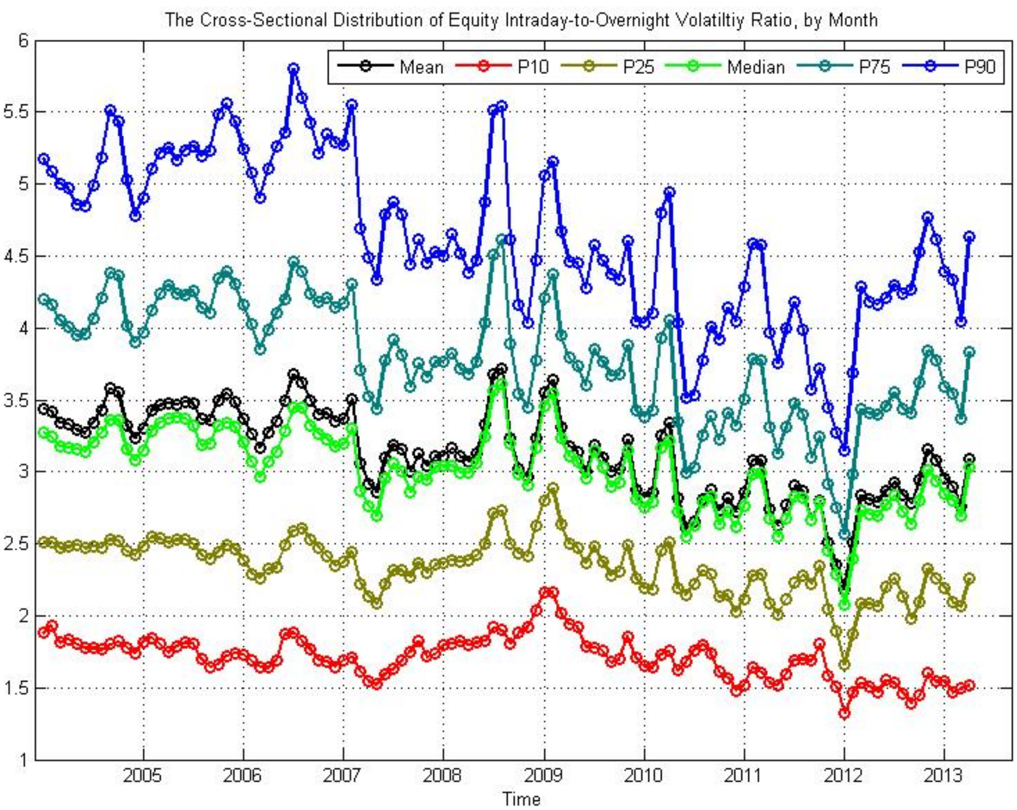

Figure A.3 Day and night option returns in the Black-Scholes-Merton model

We study how day and night option returns depend on the volatility bias in the BSM model. We show average option returns for different levels of the day-night volatility ratio ($\sigma_{day}/\sigma_{night} = 1.6, 2.5, 3.3, 4.1$), covering plausible values in the data. Each graph shows how day and night returns depend on the degree to which option prices underreact to day-night volatility seasonality. While the actual seasonality is $\lambda = \sigma_{day}/\sigma_{night}$, option prices are set assuming a different ratio $\lambda^{IV} = \sigma_{day}^{IV}/\sigma_{night}^{IV}$. In *Full Bias* case $\lambda^{IV} = 1$, option prices completely ignore volatility seasonality and $\sigma_{day}^{IV} = \sigma_{night}^{IV} = \sigma^{IV}$. In "No Bias" case, option prices are set using the correct volatility ratio $\lambda^{IV} = \lambda$.

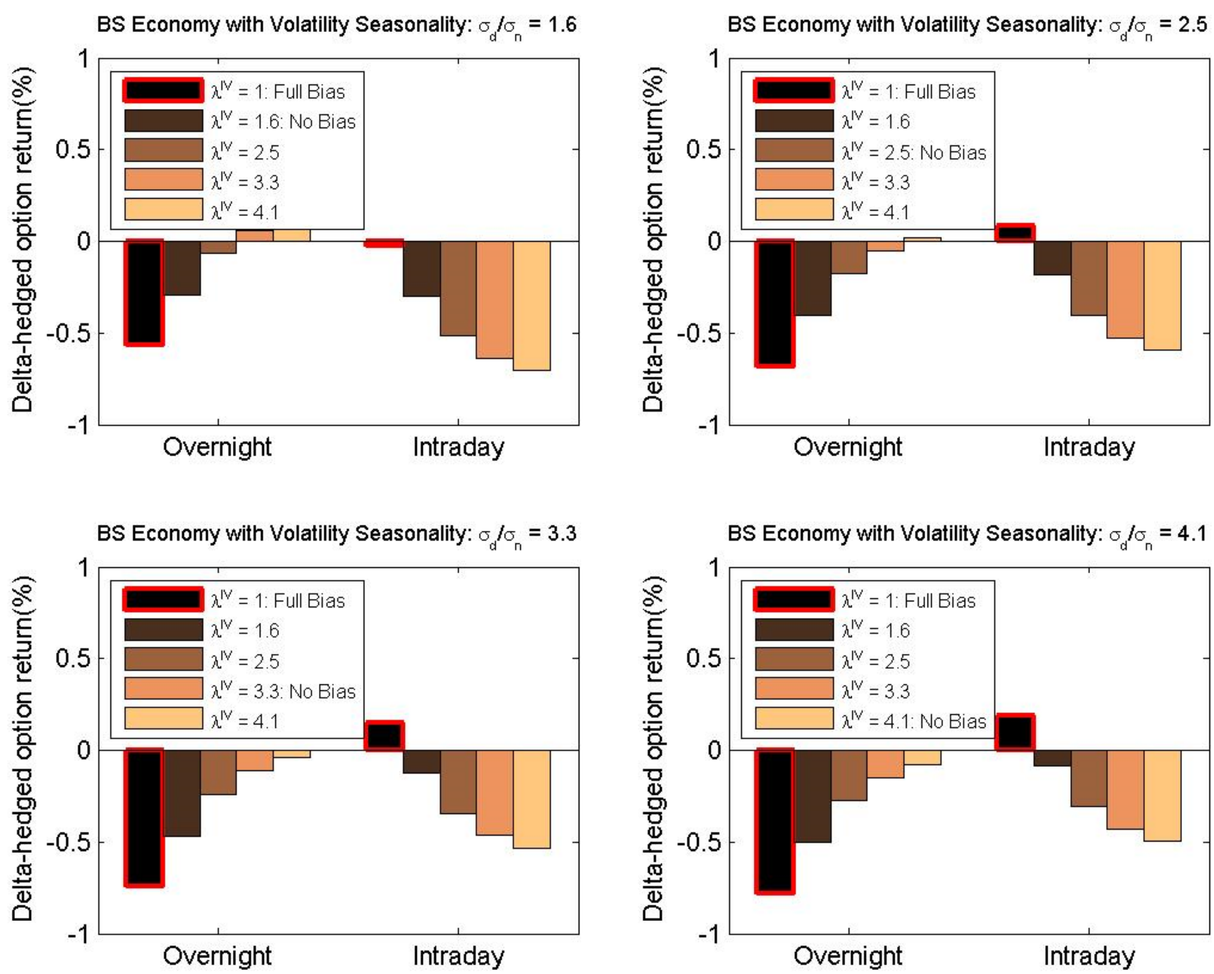

Table A.1 Summary statistics for day and night returns for S&P500 index and individual stocks

Returns and variances are not annualized and not adjusted for the difference in length between intraday and overnight periods.

Panel A. S&P500 index returns

	Mean	Std. Dev.	Skewness	Ex. Kurt.	5%	50%	95%
Intraday	0.00%	0.009	-0.264	14.375	-1.35%	0.05%	1.14%
Overnight	0.01%	0.006	-0.055	18.970	-0.92%	0.03%	0.81%

Panel B. Equity returns

	Mean	Std. Dev.	Skewness	Ex. Kurt.	5%	50%	95%
Intraday	0.00%	0.031	0.569	20.314	-4.25%	-0.05%	4.35%
Overnight	0.06%	0.021	1.616	61.836	-2.55%	0.02%	2.77%

Table A.2 Option returns by year.

Panel A. Returns for equity options

Year	Average Returns, %								T-statistics		
	Intraday Subperiod						Night	Diff.	Day	Night	Diff.
	1st	2nd	3rd	4th	5th	Total	Total	Day - Night	Total	Total	Day - Night
2004	0.08	-0.02	-0.05	0.02	0.10	0.13	-0.30	0.43	1.7	-10.7	5.4
2005	0.10	-0.02	-0.03	0.01	0.10	0.17	-0.34	0.51	2.4	-13.2	7.0
2006	0.16	-0.03	-0.01	0.00	0.05	0.18	-0.50	0.68	2.5	-20.4	9.5
2007	0.23	0.03	0.04	0.03	0.14	0.47	-0.50	0.97	3.8	-11.0	8.0
2008	0.23	0.10	0.03	0.09	0.15	0.60	-0.35	0.97	3.2	-3.5	5.2
2009	0.04	-0.07	-0.05	-0.10	0.02	-0.16	-0.49	0.30	-1.5	-8.2	2.1
2010	0.05	-0.05	-0.11	-0.03	0.05	-0.08	-0.47	0.39	-0.6	-6.1	2.5
2011	0.08	-0.02	-0.03	0.06	0.06	0.15	-0.48	0.63	0.9	-5.3	3.3
2012	0.08	-0.07	-0.10	0.00	-0.02	-0.11	-0.45	0.35	-1.2	-7.3	3.0
2013	0.12	-0.04	-0.07	0.00	0.10	0.11	-0.50	0.61	0.5	-4.7	2.3

Panel B. Returns for major ETF options.

The returns are based on average returns for three ETF options: S&P 500 (SPY), NASDAQ 100 (QQQ), and Russell 2000 (IWM). These three ETFs have the most active trading in options. Intraday returns are positive in all years except for -0.17% in 2004 and -0.05% in 2012.

Year	Average Returns, %								T-statistics		
	Intraday Subperiod						Night	Diff.	Day	Night	Diff.
	1st	2nd	3rd	4th	5th	Total	Total	Day - Night	Total	Total	Day - Night
2004	-0.11	-0.06	-0.09	0.01	0.09	-0.17	-0.51	0.33	-1.8	-10.9	3.2
2005	-0.02	-0.05	-0.06	0.02	0.14	0.03	-0.52	0.55	0.3	-12.5	4.5
2006	0.12	-0.07	0.04	0.05	0.02	0.16	-0.48	0.63	1.3	-9.8	5.0
2007	0.03	-0.01	0.10	0.13	0.12	0.37	-0.44	0.83	2.4	-4.6	4.7
2008	0.01	0.03	0.07	0.18	0.18	0.47	-0.27	0.78	2.6	-2.2	3.8
2009	0.09	0.04	-0.04	-0.10	0.02	0.01	-0.52	0.50	0.1	-7.1	3.2
2010	0.06	-0.01	-0.05	0.04	0.11	0.14	-0.54	0.67	0.9	-4.9	3.2
2011	0.06	0.08	-0.01	0.11	0.06	0.30	-0.47	0.77	1.8	-3.7	3.6
2012	0.08	-0.03	-0.07	0.04	-0.06	-0.05	-0.52	0.47	-0.5	-5.3	3.2
2013	0.28	-0.10	-0.12	-0.02	0.11	0.16	-0.76	0.93	0.6	-5.0	2.5
Total	0.04	-0.01	-0.02	0.05	0.08	0.14	-0.48	0.63	3.1	-16.3	11.3

Table A.3 Leverage-adjusted returns for S&P 500 index options by moneyness and time-to-expiration

Option delta hedged returns are adjusted for implied leverage as described at the end of Section 3. Moneyness is measured as absolute option delta. Maturity is measured as trading days before expiration. Returns are in percentage points per day(e.g., 0.73%) daily return for short term index options intraday. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment.

Moneyness (|Δ|) and Maturity (Days)	Average Returns, %					T-statistics				
	4-15	16-53	54-118	119-252	253+	4-15	16-53	54-118	119-252	253+
Intraday:										
0.1 < |Δ| < 0.25	0.023	0.015	0.007	0.013	0.031	2.0	1.6	0.8	1.3	2.4
0.25 < |Δ| < 0.5	0.025	0.014	0.013	0.019	0.025	3.3	2.4	2.2	2.8	2.9
0.5 < |Δ| < 0.75	0.015	0.010	0.008	0.009	0.014	3.5	2.7	2.0	2.0	2.3
0.75 < |Δ| < 0.9	0.006	0.003	0.002	0.007	0.014	2.5	1.5	0.9	1.6	2.0
Overnight:										
0.1 < |Δ| < 0.25	-0.102	-0.057	-0.041	-0.042	-0.053	-13.5	-9.4	-7.4	-7.3	-5.8
0.25 < |Δ| < 0.5	-0.063	-0.042	-0.033	-0.033	-0.030	-12.7	-10.2	-9.5	-8.9	-5.9
0.5 < |Δ| < 0.75	-0.038	-0.026	-0.022	-0.022	-0.023	-13.2	-11.5	-8.6	-7.4	-6.0
0.75 < |Δ| < 0.9	-0.018	-0.015	-0.010	-0.006	-0.014	-10.3	-9.9	-3.6	-1.3	-1.6

Table A.4 Option returns by time-to-expiration

Maturity is measured as the number of trading days before expiration. Each trading day is divided into five equal subperiods. "Total" column for intraday returns reports the cumulative sum of subperiod returns. Returns are in percentage points per day (e.g., a 0.73%) daily return for short-term index options intraday. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

Maturity, Days	Average Returns, %							T-statistics						
	Intraday Subperiod						Overnight	Intraday						Overnight
	1st	2nd	3rd	4th	5th	Total	Total	1st	2nd	3rd	4th	5th	Total	Total
S&P Options														
4-15	0.01	0.01	-0.11	0.36	0.41	0.73	-2.62	0.1	0.1	-1.7	4.4	3.4	3.1	-15.6
16-53	-0.07	-0.05	-0.01	0.17	0.24	0.29	-1.00	-1.1	-1.1	-0.2	4.2	4.1	2.4	-12.1
54-118	-0.03	0.00	-0.01	0.10	0.10	0.16	-0.47	-0.7	0.1	-0.5	3.5	2.1	1.8	-8.7
119-252	0.02	0.02	0.01	0.07	0.08	0.16	-0.29	0.5	0.9	0.5	2.9	2.4	2.6	-8.4
253+	0.02	0.04	0.02	0.05	0.08	0.21	-0.22	0.6	1.5	0.8	2.0	2.3	3.1	-6.5
Equity Options														
4-15	0.24	-0.04	-0.13	-0.04	0.00	0.04	-1.01	7.9	-1.7	-7.8	-2.0	0.1	0.5	-18.5
16-53	0.15	-0.02	-0.05	0.01	0.07	0.17	-0.51	9.4	-1.5	-6.1	0.8	6.7	4.2	-20.4
54-118	0.09	0.00	-0.01	0.02	0.07	0.18	-0.21	7.4	0.3	-1.6	2.2	7.1	5.6	-11.5
119-252	0.06	0.00	-0.01	0.02	0.06	0.13	-0.09	5.0	0.2	-1.3	2.4	6.3	4.6	-5.8
253+	0.07	0.02	0.00	0.01	0.03	0.13	-0.05	5.7	1.8	-0.2	1.3	3.1	4.8	-3.2

Table A.5 S&P 500 index option returns double-sorted by (normalized) option Theta and Vega

This table reports intraday and overnight option returns of portfolios double sorted by option Theta and Vega. Theta is computed as $\partial C/\partial t$, and Vega is computed as $\partial C/\partial \sigma$, where C is the option price. Theta and Vega of each option are measured at the start of each period. We then independently sort options into 4 groups by Theta and Vega, with 16 portfolios in total. Option returns are reported in percentage points per day. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment.

Double-sorted by Theta and Vega	**Average Returns, %**					**T-statistics**				
	$Vega_{Low}$	$Vega_2$	$Vega_3$	$Vega_{High}$	$Vega_{All}$	$Vega_{Low}$	$Vega_2$	$Vega_3$	$Vega_{High}$	$Vega_{All}$
Intraday:										
$Theta_{Low}$	0.25	0.39	0.35	0.41	0.38	2.4	2.9	2.1	2.0	2.2
$Theta_2$	0.17	0.20	0.14	0.15	0.15	3.4	2.7	1.4	1.2	1.7
$Theta_3$	0.07	0.14	0.11	0.17	0.11	1.9	2.5	1.6	1.7	2.0
$Theta_{High}$	0.03	0.09	0.14	0.15	0.09	1.4	2.5	2.8	1.5	2.4
$Theta_{All}$	0.09	0.16	0.19	0.30	0.18	2.3	2.7	2.0	1.9	2.1
Overnight:										
$Theta_{Low}$	-1.11	-1.70	-1.90	-2.04	-1.92	-13.2	-16.1	-17.0	-15.0	-16.2
$Theta_2$	-0.63	-0.72	-0.74	-0.74	-0.74	-15.1	-15.1	-12.4	-8.8	-12.8
$Theta_3$	-0.34	-0.36	-0.39	-0.37	-0.38	-13.6	-10.9	-9.2	-5.6	-10.5
$Theta_{High}$	-0.12	-0.17	-0.24	-0.30	-0.17	-6.6	-7.9	-8.0	-3.7	-7.7
$Theta_{All}$	-0.46	-0.63	-0.96	-1.53	-0.92	-14.3	-10.9	-14.5	-14.5	-14.3

Table A.6 Volatility and equity risk cannot explain day-night option returns

The table reports a time series regression of S&P 5000 delta hedged index option returns on the index returns (Panel A) and VIX futures returns (Panel B). Index and VIX futures returns are computed over exactly the same period as option returns (e.g., open-to-close for intraday). We report results separately for intraday and overnight returns. VIX futures returns are computed at the same open and close times as for index options. Returns are in percentage points per day (e.g., the intercept of "0.18" means an 0.18% daily abnormal alpha). T-statistics are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

Panel A: $OptRet_t = a + b * Ret_t + \epsilon_t$

	Intraday		Overnight	
	a	b	a	b
Coeff.	0.18	-2.07	-0.99	-3.33
T-stat.	2.1	-10.2	-18.4	-10.4

Panel B: $OptRet_t = a + b * Ret_t + c * VIXFutRet_t + \epsilon_t$

	Intraday			Overnight		
	a	b	c	a	b	c
Coeff.	0.24	0.08	0.92	-0.89	-1.63	0.66
T-stat.	3.2	0.5	17.3	-12.8	-2.6	5.6

Table A.7 Unhedged returns and straddle returns for S&P 500 index options

We explore the robustness of our main result by computing option returns in two alternative ways that do not require delta-hedging in the underlying. Panel A reports returns for a straddle portfolio that includes a call and as many corresponding puts (with the same strike and expiration) requisite to make it delta-neutral. On average, a straddle portfolio has one call and one put. Panel B reports raw option returns (i.e., returns are computed the same way as in the baseline case except no delta-hedging is done). Returns are in percentage points per day (e.g., "0.18" means an 0.18% daily return). Intraday period is divided into five equally long subperiods.

Panel A Straddle returns

	Return Average, %							T-statistics						
	Intraday Subperiods						Overnight	Intraday Subperiods						Overnight
	1st	2nd	3rd	4th	5th	Total	Total	1st	2nd	3rd	4th	5th	Total	Total
All Deltas	-0.03	-0.02	-0.02	0.11	0.14	0.18	-0.85	-0.9	-0.9	-0.8	4.3	3.9	2.5	-17.7
0.1 < |Δ| < 0.25	0.03	-0.01	-0.04	0.15	0.13	0.26	-1.00	0.5	-0.2	-1.2	3.9	2.8	2.7	-14.1
0.25 < |Δ| < 0.5	0.03	0.00	-0.02	0.13	0.16	0.30	-0.91	0.7	0.0	-0.7	4.7	4.0	3.9	-16.5
0.5 < |Δ| < 0.75	-0.01	-0.02	0.00	0.10	0.11	0.19	-0.73	-0.2	-0.8	-0.1	4.5	4.0	3.1	-17.0
0.75 < |Δ| < 0.9	-0.10	-0.04	-0.02	0.12	0.13	0.09	-0.89	-3.0	-1.5	-0.8	4.3	3.8	1.2	-16.6

Panel B Unhedged returns

	Return Average, %							T-statistics						
	Intraday Subperiods						Overnight	Intraday Subperiods						Overnight
	1st	2nd	3rd	4th	5th	Total	Total	1st	2nd	3rd	4th	5th	Total	Total
All	-0.04	-0.03	-0.02	0.14	0.16	0.22	-0.93	-0.8	-0.8	-0.7	4.1	3.6	2.3	-12.1
Puts	0.13	0.05	-0.10	0.15	0.00	0.31	-1.16	0.8	0.4	-1.0	1.1	0.0	0.9	-4.6
Calls	-0.17	-0.07	0.07	0.18	0.32	0.39	-0.63	-1.2	-0.6	0.7	1.5	2.0	1.3	-3.1

Table A.8 Trade price as an alternative to the option quote midpoint

Panel A compares trade price with a quote midpoint at the time of the trade for S&P500 index options. For all option trades in a given sup-period and day, we compute the average dollar difference $(TP_i - Mid_i)$ and relative difference $(TP_i - Mid_i)/Mid_i$ between trade price and quote midpoint. We then compute the average across days. ("0.0024" means 0.24 cents.) Panel B reports day and night option returns computed from trade prices. For a set of options that trade around both open and close, we compute option delta hedged returns the same way as for the quote midpoints (i.e., delta-hedging, etc.).

Panel A Average difference between option trade prices and the quote midpoints

	Intraday Subperiod					
	1st	2nd	3rd	4th	5th	Overall
Dollar Difference, $	0.0024	0.0032	0.0067	0.0088	0.0099	0.0063
Relative Difference, %	0.07	0.07	0.08	0.10	0.12	0.09

Panel B Day and night option returns computed from option trade prices

		Return Average, %			T-statistics		
		Intraday	Overnight		Intraday	Overnight	
		Total	Total	Exclude Weekends	Total	Total	Exclude Weekends
All	All Deltas	0.44	-2.26	-1.82	2.8	-17.8	-14.0
	0.1 < |Δ| < 0.25	0.62	-3.84	-3.10	2.3	-18.7	-14.7
	0.25 < |Δ| < 0.5	0.43	-1.98	-1.67	3.2	-18.7	-15.5
	0.5 < |Δ| < 0.75	0.32	-0.69	-0.45	4.0	-9.8	-6.1
	0.75 < |Δ| < 0.9	0.27	-0.03	0.06	3.8	-0.3	0.4
Puts	All Deltas	0.40	-2.32	-1.96	2.6	-17.2	-14.1
Calls	All Deltas	0.48	-2.41	-1.83	2.7	-14.7	-10.7

Table A.9 S&P 500 index option returns using alternative open and close option prices

This table reports intraday- and overnight-option returns using alternative definitions of open and close option prices. In particular, we compute option returns using (i) a 10 a.m. quote midpoint as the open price, (ii) a 4 p.m. quote midpoint as the close price (index options close at 4:15p.m.); we then (iii) compute returns using only option bid prices and (iv) using only ask prices. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

	Option Returns		**T-statistics**	
Option Price	**Intraday**	**Overnight**	**Intraday**	**Overnight**
Open at 10am	0.29%	-1.17%	3.4	-16.7
Close at 4pm	0.20%	-1.08%	2.3	-16.1
Option Bid	0.27%	-1.08%	2.9	-14.2
Option Ask	0.22%	-0.96%	2.4	-13.5

Table A.10 VIX futures day and night returns

Maturity is measured in trading days to expiration. First, we compute average return for all futures in a given maturity bin on a given day and then the average return across days. Returns are computed using the quote midpoints and are reported in percentage points per day (e.g., "0.11" means a 0.11% daily return). VIX futures returns are computed at the same open and close times as for index options. Intraday period is divided into five equally long subperiods. An overnight period is from 4:15 pm to 9:30 am. to match the options results. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment.

Maturity, days	Return Average, %							T-statistics						
	Intraday Subperiods						Overnight	Intraday Subperiods						Overnight
	1st	2nd	3rd	4th	5th	**Total**	**Total**	1st	2nd	3rd	4th	5th	**Total**	**Total**
Front-month	0.06	0.03	0.00	0.01	-0.10	0.01	-0.15	1.3	1.0	0.0	0.3	-2.7	0.1	-2.6
4-15	0.11	-0.02	0.05	0.01	-0.10	0.04	-0.20	1.7	-0.5	1.1	0.3	-1.9	0.4	-2.4
16-53	0.03	0.03	-0.01	0.02	-0.01	0.06	-0.15	0.8	1.0	-0.2	1.0	-0.5	1.0	-3.3
54-118	0.00	0.03	0.01	0.03	0.02	0.08	-0.09	-0.2	1.6	0.4	1.7	1.0	2.0	-2.7
119-252	-0.05	0.00	0.00	0.02	0.05	0.02	0.04	-2.1	0.3	0.0	1.4	1.6	0.5	0.9
253+	-0.02	0.00	0.01	0.00	-0.01	-0.02	-0.03	-1.6	-0.5	0.6	0.2	-1.2	-1.1	-1.9

Table A.11 Panel A Portfolio sorts for S&P 500 index option returns

Time series of S&P index option returns for overnight and intraday periods are sorted into four equally weighted portfolios. Option liquidity is measured as the option effective bid-ask spread. The AAII Investor Sentiment Survey measures the percentage of individual investors who are bullish, bearish, and neutral on the stock market. "BW Sentiment" is the Baker and Wurgler (2006) index of investor sentiment.

VIX Index	Intraday	Overnight	Diff	t-stat
Low, 1	-0.28	-0.86	0.58	4.9
2	-0.02	-1.03	1.02	5.3
3	0.08	-1.07	1.15	5.0
High, 4	0.97	-1.14	2.12	6.9
H - L	-1.26	0.28		
t-stat	-5.3	1.2		

LIBOR	Intraday	Overnight	Diff	t-stat
Low, 1	0.12	-1.26	1.38	6.3
2	0.05	-0.98	1.03	4.4
3	0.25	-0.94	1.18	5.0
High, 4	0.33	-0.91	1.24	6.2
H - L	-0.21	-0.36		
t-stat	-0.9	-2.2		

TED Spread	Intraday	Overnight	Diff	t-stat
Low, 1	0.20	-1.26	1.46	6.8
2	0.01	-0.93	0.94	4.2
3	0.17	-1.01	1.18	6.3
High, 4	0.42	-0.93	1.34	4.9
H - L	-0.22	-0.34		
t-stat	-0.8	-1.5		

Option Liquidity	Intraday	Overnight	Diff	t-stat
Low, 1	-0.01	-1.05	1.05	6.0
2	0.04	-1.04	1.08	6.5
3	0.15	-1.07	1.22	6.1
High, 4	0.57	-0.94	1.51	4.8
H - L	-0.58	-0.11		
t-stat	-2.1	-0.5		

AAII Sentiment	Intraday	Overnight	Diff	t-stat
Low, 1	0.66	-1.13	1.79	6.7
2	0.02	-1.04	1.06	4.8
3	0.20	-1.12	1.32	6.1
High, 4	-0.14	-0.82	0.69	3.9
H - L	0.80	-0.30		
t-stat	3.4	-1.4		

BW Sentiment	Intraday	Overnight	Diff	t-stat
Low, 1	0.08	-1.23	1.30	6.6
2	-0.27	-0.96	0.69	3.2
3	0.21	-1.09	1.30	6.8
High, 4	0.70	-0.68	1.38	4.1
H - L	-0.62	-0.54		
t-stat	-2.1	-2.1		

Table A.11 Panel B Portfolio sorts for S&P 500 index option returns based on tail risk measures

Time series of S&P index option returns for overnight and intraday periods are sorted into four equally weighted portfolios based on measures of tail risk. *KJ* is the tail risk measure proposed by Kelly and Jiang (2014). *DK* is the jump tail risk measure introduced by Du and Kapadia (2012). The t-statistics are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

KJ Measure	Intraday	Overnight	Diff	t-stat
Low, 1	-0.07	-1.13	1.06	5.4
2	0.51	-0.75	1.26	4.9
3	0.24	-1.00	1.24	5.8
High, 4	0.07	-1.23	1.30	6.0
H - L	0.13	-0.11		
t-stat	0.6	-0.6		

DK Measure	Intraday	Overnight	Diff	t-stat
Low, 1	0.18	-0.91	1.09	6.5
2	0.22	-1.02	1.23	6.0
3	0.25	-0.91	1.16	4.5
High, 4	0.13	-1.10	1.24	4.2
H - L	-0.04	-0.19		
t-stat	-0.2	-0.8		

Table A.12 Time series predictability for S&P500 options

Time series of day and night returns for S&P 500 index options and their difference are regressed on controls from the previous day, including day-night volatility ratio, absolute stock return as a proxy for realized volatility, option bid-ask spread, implied volatility, volatility skew, variance risk-premium, implied volatility spread between calls and puts, and option order imbalance computed from open-close and intraday data. Each regression is based on 2298 daily return observations. The t-statistics in parentheses are computed using Newey-West (1987).

	$OptReturn_{t+1}$, %		
	Day	Night	Day - Night
$Intercept$	-0.508	-1.203	0.682
	(-1.00)	(-2.16)	(0.86)
$\sigma_{day}/\sigma_{night}$	0.137	0.090	0.049
	(0.80)	(0.68)	(0.22)
$AbsStkRet_t$	3.003	-1.253	4.271
	(1.14)	(-0.47)	(1.02)
$OptBidAskSpread_t$	-1.609	-0.103	-1.506
	(-0.24)	(-0.02)	(-0.18)
$Implied\ Volatility_t$	-16.539	3.327	-19.875
	(-1.09)	(0.23)	(-0.86)
$IV\ Skew_t$	-1.175	12.791	-14.142
	(-0.13)	(1.08)	(-0.87)
$VarRiskPrem_t$	2.577	-1.073	3.671
	(0.99)	(-0.40)	(0.88)
$IV\ Spread_t$	-2.151	-17.147	14.894
	(-0.30)	**(-2.42)**	(1.46)
$OImb\_OpenClose_t$	5.646	-0.963	6.62
	(2.11)	(-0.49)	(1.99)
$OImb\_Intraday_t$	1.365	-2.948	4.313
	(0.70)	**(-2.31)**	(1.89)
R^2, %	0.85	2.71	2.31

Table A.13 Intraday volatility seasonality test

Panel A. Intraday seasonality in equity option returns. The table reports Fama-MacBeth regressions for equity option returns for three intraday subperiods (morning, noon, and afternoon) on just the intercept, which corresponds to average option return for a given subperiod (i.e., 0.139% return per day). The last two columns show the difference between intraday returns.

	Morning	Mid-day	Afternoon	Morn.-Midday	After.-Midday
Intercept	0.139	-0.041	0.059	0.181	0.1
	(6.89)	(-3.63)	(3.91)	(10.11)	(7.56)

Panel B. Intraday seasonality in equity volatility. The table reports Fama-MacBeth regressions of the volatility ratio between intraday subperiods on the intercept. I.e., afternoon volatility is 20% higher than mid-day volatility, hence a 1.20 coefficient.

	$\sigma_{morn}/\sigma_{mid}$	$\sigma_{aftern}/\sigma_{mid}$
Intercept	1.78	1.20
	(10.11)	(7.56)

Panel C. The main test. Can intraday volatility seasonality explain variation in intraday option returns across stocks? Similarly to the day-night test in Table 8, option returns in a particular intraday subperiod (e.g., morning and noon) or their difference is regressed on the corresponding volatility ratio (e.g., morning vol. to noon vol.). Volatility ratios are estimated out-of-sample based on subperiod stock returns over the preceding 60 days. The fourth and last columns add several controls.

	Morn.	Mid-day	Morn.-Mid.	Morn.-Mid.	Mid-day	After.	After.-Mid.	After.-Mid.
Intercept	0.015	-0.018	0.034	0.016	-0.017	-0.027	-0.01	-0.036
	(0.53)	(-1.20)	(1.16)	(0.50)	(-1.37)	(-1.83)	(-0.62)	(-1.69)
$\sigma_{morn}/\sigma_{mid}$	0.07	-0.013	0.083	0.082				
	(6.57)	(-2.57)	(7.27)	(7.36)				
$\sigma_{aftern}/\sigma_{mid}$					-0.02	0.069	0.089	0.086
					(-2.51)	(6.48)	(6.81)	(6.81)
Controls	-	-	-	+	-	-	-	+
$Adj.R^2$ (%)	0.12	0.09	0.13	1.63	0.15	0.25	0.22	1.48

Table A.14 Day-night cross-stock test for the subsample of stocks with low option volume

In this table, we conduct a cross-sectional test for the day-night volatility in Table 8 for the subsample with little option trading volume. Specifically, we consider 30% of optionable stocks with the lowest option trading volume, thus option price pressure is economically small in this sample. The results are very similar to the full sample test in Table 8. The first two columns report separate Fama-MacBeth regressions for day-night option returns on just the intercept. Trying to explain these intercepts/returns, return regressions in the next two columns control for just the day-night volatility ratio. For the volatility ratio, we first compute intraday (overnight) volatility from open-to-close (close-to-open) stock returns from the preceding 60 days, annualize both volatilities, and then compute their ratio. The last two columns add several controls, including absolute stock return, option bid-ask spread, option volume, option implied volatility, volatility skew, option volume, variance risk premium, and implied volatility spread between calls and puts. Returns are in percentage points per day (e.g., 0.16 is 0.16% per day). T-statistics in brackets are computed using the Newey-West (1987) adjustment.

	$Option\ Return_{t+1}, \%$					
	Day	Night	Day	Night	Day	Night
Intercept	0.16	-0.62	-0.23	-0.30	-0.05	-0.36
	(2.4)	(-18.9)	(-3.3)	(-3.6)	(-0.3)	(-2.0)
$\sigma_{day}/\sigma_{night}$			0.13	-0.10	0.18	-0.09
			(11.9)	(-4.5)	(3.9)	(-4.5)
Controls	-	-	-	-	+	+
$Adj. R^2, \%$	0.00	0.00	0.34	0.38	3.60	3.79

Table A.15 Parameter choices: data versus model

Panel A the BSM model. We adjust the standard BSM model to add the day-night volatility seasonality and report our main parameter choices in this table. The data moments are computed using sample of S&P500 index from January 2004 to December 2013. In the model, μ is the instantaneous return (annualized) of the underlying asset. r_f is the risk-free rate (annualized). σ is the instantaneous volatility for the asset price process, scaled to daily level. σ^{IV} is the implied volatility used to price options. We choose $\sigma^{IV} > \sigma$ to match the average daily delta hedged option returns on S&P500 index, which is approximately -0.7%.

	Data	Model
μ, annual	5.08%	5.08%
σ, annual	14.88%	14.88%
r_f, annual	1.52%	1.52%
σ^{IV}, annual	-	21%

Panel B the Heston model. The panel reports key parameters of the Heston model adjusted for the day-night volatility seasonality. μ is the instantaneous drift of the return process for the underlying. r_f is the risk-free rate. For the instantaneous stochastic variance process V_t, κ is its mean-reverting speed, θ is the long-run variance, η is the volatility of volatility. γ is the price of volatility risk. ρ is the correlation between innovations in asset price and stochastic volatility. Source: 1 – from the data. 2 – parameter estimation from Broadie et al. (2007). 3 – based on Broadie et al. (2007), we adjust parameters by amplifying with same multiples to get comparable magnitude in our benchmark case.

	Data	Model	Source*
μ	5.08%	5.08%	1
r_f	1.52%	1.52%	1
κ	-	34.27	3
θ	-	2.21%	1
η	-	0.28	2
γ	-	-20.16	3
ρ	-	-0.37	2

Table A.16 Confirming cross-sectional tests for panel of simulated option returns

This table reports Fama-MacBeth cross-sectional regressions on a panel of simulated option returns. These simulations validate our tests for volatility bias in Table 8. We simulate option returns in the BSM model for a cross-section of stocks with the day-night volatility ratio ranging between 1.5 to 5, to match the 10% to 90% percentiles of the cross-sectional distribution in the data in Figure A.2. Option prices are computed assuming that instantaneous volatility is the same intraday and overnight. Panel A reports Fama-MacBeth regression of day and night option returns on the volatility ratio. T-statistics are reported in parentheses are large because we can simulate a large panel. The option return is reported in percentage points (e.g., -0.11%). Panel B confirms that the absolute value of the coefficients for the day-night volatility ratio are not statistically different. These results for simulated returns are remarkably similar to the results for actual data in Table 8.

Panel A

	$OptRet_{Intraday}$, %		$OptRet_{Overnight}$, %	
Constant	0.16	-0.11	-0.90	-0.63
	(15.3)	(-20.1)	(-277.1)	(-75.9)
$\lambda = \sigma_{day}/\sigma_{night}$		0.08		-0.08
		(54.1)		(-53.0)

Panel B

H_0:	$\beta^{\lambda}_{day} = -\beta^{\lambda}_{night}$
p-value:	0.82
Reject or not?	Cannot reject H_0

Table A.17 Maturity bias and option returns

Panel A. Day and night option returns under maturity bias. Panel A reports average intraday and overnight option returns simulated from the Heston model with the maturity bias. We first simulate the model without the variance risk premium ("no VRP") to confirm that according to the maturity bias, day and night returns offset each other in this case. We then consider the Heston model with variance premium and the maturity bias ("with VRP"). We use the same realistic parameter values as in Table A.15 to match average daily returns.

Option Ret.	Day	Night
no VRP	0.57%	-0.58%
with VRP	0.02%	-0.82%

Panel B. Maturity bias and stock volatility. Panel B simulates option returns under the maturity bias and without VRP. It then reports average intraday option returns by maturity and moneyness for two levels of stock volatility, $\sigma = 15\%$ and $\sigma = 30\%$. According to the maturity bias, day-night option returns depend little on the underlying volatility. To save space, we only report intraday returns, as overnight returns have the same magnitude but the opposite sign (no VRP).

$\boldsymbol{\sigma = 15}\%$	4-15 days	16-53 days	54-118 days	119-252 days
All Deltas	1.89%	0.55%	0.24%	0.07%
0.1 < |D| < 0.25	4.07%	1.20%	0.54%	0.16%
0.25 < |D| < 0.5	2.10%	0.63%	0.28%	0.09%
0.5 < |D| < 0.75	1.02%	0.27%	0.12%	0.04%
0.75 < |D| < 0.9	0.35%	0.10%	0.05%	0.02%

$\boldsymbol{\sigma = 30}\%$	4-15 days	16-53 days	54-118 days	119-252 days
All Deltas	1.90%	0.53%	0.22%	0.07%
0.1 < |D| < 0.25	4.19%	1.19%	0.49%	0.14%
0.25 < |D| < 0.5	2.19%	0.63%	0.28%	0.08%
0.5 < |D| < 0.75	0.96%	0.28%	0.13%	0.05%
0.75 < |D| < 0.9	0.35%	0.11%	0.06%	0.03%

Table A.18 Order imbalance summary statistics and correlations

Order imbalance is the difference between number of buyer and seller-initiated trades normalized by total number of trades. We compare trade price to the quote midpoint to determine trade sign in the intraday data (OPRA). For the open-close data (ISE for stocks, CBOE for S&P500), the imbalances are computed using the cumulative number of buys and sells by non-market-makers. This table reports the average, standard deviation, and number of stock-day observations, as well as the correlation table across order imbalances.

Panel A. S&P 500 Index Options

	Open-Close			Intraday		
	Calls	Puts	Total	Calls	Puts	Total
$Average$	0.2%	2.0%	1.4%	1.0%	3.4%	2.4%
$Std.Dev.$	5.6%	4.9%	3.6%	7.6%	7.2%	5.5%
$N.Obs.$	2298	2298	2298	2298	2298	2298
Correlation Table:						
$OpenClose_{Call}$	100%	-9%	46%	-2%	1%	0%
$OpenClose_{Put}$	-9%	100%	83%	8%	11%	13%
$OpenClose_{Total}$	46%	83%	100%	7%	11%	12%
$Intraday_{Call}$	-2%	8%	7%	100%	11%	67%
$Intraday_{Put}$	1%	11%	11%	11%	100%	81%
$Intraday_{Total}$	0%	13%	12%	67%	81%	100%

Panel B. Equity Options

	Open-Close			Intraday		
	Calls	Puts	Total	Calls	Puts	Total
$Average$	-1.5%	0.5%	-1.1%	-2.1%	-0.6%	-2.7%
$Std.Dev.$	31.6%	26.4%	41.3%	34.5%	27.3%	44.7%
$N.Obs.$	2040754	2040754	2040754	2040754	2040754	2040754
Correlation Table:						
$OpenClose_{Call}$	100%	1%	77%	21%	3%	18%
$OpenClose_{Put}$	1%	100%	64%	3%	25%	17%
$OpenClose_{Total}$	77%	64%	100%	18%	18%	25%
$Intraday_{Call}$	21%	3%	18%	100%	4%	79%
$Intraday_{Put}$	3%	25%	18%	4%	100%	64%
$Intraday_{Total}$	18%	17%	25%	79%	64%	100%

Table A.19 Order imbalances by year

The imbalance for each year is computed as an average of daily imbalances. Imbalances are reported in percentage points (e.g., 5.68 means 5.68%). Table A.16 describes how imbalances are computed.

Panel A. S&P 500 Index Options

Year	Intraday			Open-Close		
	Call	Put	Total	Call	Put	Total
2004	5.68	8.51	7.30	0.44	3.22	2.16
2005	2.79	4.95	4.07	0.96	3.58	2.60
2006	-1.73	1.10	-0.03	0.41	2.43	1.60
2007	-1.70	0.14	-0.54	-0.26	2.63	1.67
2008	-0.77	0.01	-0.29	1.61	1.18	1.29
2009	0.34	2.20	1.37	0.11	0.71	0.55
2010	1.40	2.75	2.03	-0.23	1.38	0.88
2011	-0.32	2.61	1.35	0.19	1.48	1.03
2012	-0.23	3.68	1.87	-1.00	1.60	0.67
2013	0.29	5.90	3.33	-1.55	1.00	0.05

Panel B. Equity Options

Year	Intraday			Open-Close		
	Call	Put	Total	Call	Put	Total
2004	-5.46	-1.37	-6.82			
2005	-4.92	-0.94	-5.86	-1.37	-0.38	-1.74
2006	-3.54	-0.14	-3.68	-1.57	-0.04	-1.61
2007	-2.48	0.66	-1.82	-1.15	-0.08	-1.23
2008	-1.11	1.73	0.62	-1.92	0.01	-1.91
2009	-1.09	0.19	-0.90	-2.17	-1.49	-3.66
2010	-1.15	0.28	-0.87	-3.22	-1.44	-4.66
2011	-1.59	0.55	-1.04	-2.75	-0.73	-3.48
2012	-1.73	0.07	-1.65	-1.66	-0.51	-2.17
2013	-1.68	-0.63	-2.31			

Table A.20 Trading strategy

We compare overnight returns for SPY options with their trading costs. We follow Muravyev and Person (2017) in using the adjusted effective bid-ask spreads for two investor types. "Algo" denotes option trades that are likely initiated by smart execution algorithms ("Non-Algo" reflects all trades excluding algo trades; their trading costs are equal to the conventional effective bid-ask spread). "Combined" includes all trades, both algo and non-algo. We report results for two subperiods: before and after the tick size for SPY options was reduced to a penny on September 28, 2007. The last column reports profits from a hypothetical trading strategy that sells and delta hedges SPY options overnight and incurs transaction costs typical for an algo-trader.

Period	Option Overnight Returns	Trading Costs			Profits after Costs for Algos
		Non-Algo	Combined	Algo	
Pre-Penny Pilot (< Sep2007)	-0.65%	3.93%	2.25%	0.66%	-0.01%
Post-Penny Pilot (> Sep2007)	-0.64%	1.24%	0.84%	0.05%	0.60%