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

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Abstract

Average returns for S&P 500 index options are negative and large: -0.7% per day. Strikingly, when we decompose these delta-hedged option returns into intraday (open-to-close) and overnight (close-to-open) components, we find that average overnight returns are -1%, but intraday returns are actually positive, 0.3% per day. A similar return pattern holds for all maturity and moneyness categories and equity options. Most of the potential explanations struggle to explain positive intraday returns. However, our results are consistent with option prices' failing to account for the well-known fact that stock volatility is substantially higher intraday than overnight. These findings help us better understand price formation in the options market.

JEL Classification: G12, G13, G14

Keywords: Option returns, volatility seasonality, behavioral finance

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* We greatly appreciate comments from Gurdip Bakshi, Pierluigi Balduzzi, Jay Cao, Peter Ciampi, Hui Chen, Alex Chinco, Peter Christoffersen, Pasquale Della Corte, Ryan Davies, Bjorn Eraker, Mathieu Fournier, Ben Golez, Bing Han, Kris Jacobs, Michael Johannes, Cris Jones, Francis Longstaff, Loriano Mancini, Alan Marcus, George Panayotov, Neil Pearson, Jeff Pontiff, Christian Schlag, Grigory Vilkov, Liuren Wu, and Yanhui Zhao. We also thank seminar participants at Boston College, HKUST, Georgia State University, the Sixth Risk Management Conference in Mont Tremblant, the 2015 IFSID Conference on Financial Derivatives, the 2016 EFA Conference in Oslo, the 2017 Cavalcade in Nashville, the 2017 WFA Meeting in Whistler, the 2017 NFA Conference, and the 2017 FMA Meeting for their helpful comments and suggestions. We thank Nanex and Eric Hunsader for providing the trade and quote data for options and their underlying stocks. We thank Bryan Kelly and Nikunj Kapadia for providing their tail risk measures. We also thank Barry Schaudt and Boston College Research Services for computing support.

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Abstract

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1 Introduction

Derivatives play an important role in the economy. They help complete the market and allow for capital-efficient hedging and speculation. The options market is one of the world's most widely-studied, actively-traded, and transparent derivatives markets.[1] Based on these characteristics, one would expect option prices to be efficient and fair. Yet, we find that option prices are systematically biased, and positive intraday option returns are particularly hard to explain. Our results are virtually consistent with option prices' failing to account for well-known volatility seasonality: volatility is usually higher during trading hours than overnight. This conclusion is notable because volatility is a major input to option pricing models, and the models can be easily adjusted to account for the volatility seasonality. Perhaps prices in other derivatives markets may similarly deviate from their fair values, thus preventing efficient capital allocation.

To understand our main result, let us first explain the intuition behind the *average delta-hedged* option returns.[2] In the Black-Scholes-Merton (BSM) model, an option can be perfectly replicated by continuously hedging in the underlying stock. Thus, a delta-hedged option portfolio earns a risk-free rate of return. However, average option returns are negative in practice, implying that option buyers pay a risk premium to option buyers. Average option returns are also directly related to the variance risk premium: option-implied variance exceeds the realized return variance on average. Although option returns have been extensively studied,[3] there is a debate about whether these large negative returns reflect compensation for taking risk or mispricing.[4] Numerous studies show that option investors are highly sophisticated, which makes mispricing less plausible.

We contribute to the foregoing debate by documenting a noteworthy pattern in average delta-hedged option returns. In particular, option returns are only negative during the overnight period (from close to open) and are mildly positive intraday (open-to-close). Overnight delta-hedged returns are -1.0% per day for S&P 500 index options and -0.4% for equity options and are consistent over our sample period from 2004 to 2013. In contrast,

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[1] Indeed, according to Option Clearing Corporation, U.S. equity options had a notional volume of 372 trillion shares in 2015, which is about one-fifth of trading volume in U.S. equities.
[2]For brevity, henceforth, we refer to average delta-hedged option returns as simply "option returns."
[3] E.g., Bakshi and Kapadia (2003), Carr and Wu (2009), and Bakshi, Madan, and Panayotov (2010).
[4] For example, Han (2008) and Bondarenko (2014) advocate the mispricing and sentiment explanations.

during the trading day, option returns flip sign and become positive: 0.3% per day for index options and 0.1% for equity options. S&P option returns are non-negative in all intraday sub-periods. This day-night effect is stronger for options with high-embedded leverage, such as short-term and out-of-the-money options. VIX futures returns show a similar, albeit weaker, pattern. Also, this option return asymmetry varies across stocks and ETFs. That is, option returns are positive intraday for most stocks, but the pattern is reversed for some stocks with positive returns overnight. Importantly, this cross-stock variation helps us distinguish across potential explanations. We conduct numerous robustness tests. Our main results are robust to alternative definitions of open and close prices (e.g., using trade prices instead of quote midpoints), option returns (e.g., using leverage-adjusted, straddle, or raw returns), and different subsamples.

This day-night effect is not only puzzling in itself, but it also increases difficulty in explaining lucidly why option returns for S&P 500 index options are so negative, -0.7% per day in our sample.[5] Indeed, existing literature struggles to explain this fact. A common justification is that this trading strategy is akin to "picking up nickels in front of steamrollers" and lost 80% of capital during the financial crisis. However, as option returns are only negative overnight, this baseline strategy can be improved by only selling option volatility overnight and holding no position during the day. The overnight strategy increases average returns to 1.0%, more than doubles its Sharpe ratio, and is profitable in every three-month period, including the financial crisis! Admittedly, large trading costs in index options make this trading strategy hard to implement. It is potentially profitable, though, after costs in important special cases, such as the most popular index ETF, SPY.

Interestingly, option investors do not seem to take advantage of the day-night effect; perhaps most of them are simply unaware of it. Positive intraday returns encourage option investors to move their sell (buy) trades to the afternoon (morning). Contrary to this prediction, option order imbalance is stable throughout the day and, if anything, is more positive in the afternoon; that is, investors sell fewer options towards the market's close. This result may help explain why the day-night return asymmetry persists.

[5] These estimates are consistent with the prior literature that uses older data: Coval and Shumway (2001), Bakshi and Kapadia (2003), Santa-Clara and Saretto (2007), and Broadie, Chernov, and Johannes (2009) among others.

We consider a number of potential risk and friction-based explanations for the day-night return asymmetry, including stochastic volatility and price jumps, inability to adjust delta-hedges overnight, peso problem, price pressure, discretization bias, transaction costs, funding, and other carry costs. Although most of these theories help partially explain negative night returns, they are insufficient to rationalize positive intraday returns. Even zero returns are puzzling. Simply put, a delta-hedged portfolio or a straddle provides valuable insurance as either pays off during economic downturns. Stochastic volatility and jump models formalize the idea that such crash insurance should have negative expected returns. Similarly, if our sample missed an intraday rare disaster, this peso problem would worsen the intraday return puzzle. A disaster would trigger large positive returns for a delta-hedged option, and thus the true average return is even more positive than our estimate. Next, perhaps option investors consider the night particularly risky owing to inability to adjust delta-hedges and option positions. Therefore, investors seemingly require larger compensation for bearing volatility risk during the night; as such, night option returns should be particularly negative. This theory implies *less negative* intraday returns, but the returns are positive. Obviously, high option trading costs limit the ability of arbitrageurs to eliminate the day-night anomaly; however, the costs cannot explain why this effect exists in the first place.

Why most theories fail to explain sufficiently the day-night return asymmetry and its variation across stocks is facile. We test four most-promising explanations. First, the discretization bias (Branger and Schlag (2008)) argues that infrequent delta-hedging and biased option deltas may lead to positive option returns. Second, option demand pressure is a promising hypothesis because intraday option returns and order imbalances are both positive for S&P options. The limited success of rational theories encourages us to consider two behavioral explanations. The time-to-maturity bias hypothesizes that option maturity is only adjusted at the market's open instead of continuously changing throughout the day. Thus, option closing prices are too high, leading to positive intraday returns. Finally, the day-night volatility bias assumes that option prices do not correctly reflect day-night volatility seasonality.

We first focus on the volatility bias because this explanation is the most consistent with the data. The well-known fact that stock volatility is on average much higher intraday than overnight is perhaps the strongest volatility seasonality.[6] We first document how the day and night volatilities for index and stocks changed recently. The (per-hour) day-to-night volatility ratio for the S&P index remained stable, even during the crisis, and gradually decreased from three in 2004 to two in 2013. We then study how this volatility seasonality is reflected in option prices. Surprisingly, option prices are set as if day and night instantaneous volatilities are about the same, thus ignoring the seasonality. Failure to account for volatility seasonality translates into option returns. Indeed, option delta-hedged returns are proportional to the difference between realized and implied instantaneous variances (Bakshi and Kapadia, 2003). Therefore, positive intraday (negative night) returns imply that option prices understate intraday (overstate night) volatility. Even zero returns would be puzzling, because implied volatility is usually set slightly above the expected realized volatility, resulting in negative average option returns to compensate volatility-sellers for taking volatility risk.

We validate the volatility bias explanation with four major tests. First, according to this bias, stocks with more pronounced day-night volatility seasonality should have higher day-night asymmetry in option returns. That is, if options are priced assuming the same day and night volatility, while actual volatility is much higher intraday, then intraday option returns will be more positive and night return more negative. Portfolio sorts and regressions on a cross-section of more than a thousand stocks confirm this prediction. Remarkably, the day-to-night volatility ratio computed out-of-sample from historical data markedly explains the variation in the day-night option return asymmetry across stocks. Also, both day and night option returns become negative after accounting for the volatility ratio. These results suggest that volatility bias is indeed closely related to the day-night return puzzle. The second test applies a similar idea to intraday volatility seasonality. For most stocks, volatility is higher in the morning and afternoon, but the strength of this U-shaped seasonality varies across stocks. Equity option returns, on average, follow the same U-shaped pattern and are more positive in the morning and afternoon. Our main test however is cross-sectional. The ratios of morning-to-midday and afternoon-to-midday volatility

[6] Oldfield and Rogalski (1980), Amihud and Mendelson (1991), Stoll and Whaley (1990) among others.

explain variation in intraday option returns across stocks in Fama-MacBeth regressions. Specifically, the volatility ratio coefficients have the signs predicted by the bias, and the intercepts that correspond to abnormal option returns become insignificant and comparable across day and night periods. The third test is built on the idea that according to volatility bias, the day-night effect is more pronounced for shorter-term options, even after accounting for the embedded leverage. We confirm this idea in the BSM model with the bias. Consistent with test predictions, we find a similar pattern in the leverage-adjusted returns for S&P 500 index and equity options.

The final set of tests assesses whether volatility bias can produce the observed return magnitudes. We incorporate the bias in the standard BSM and Heston models and then simulate option returns from them. The models afford controlling for how much option prices underreact to volatility seasonality. In the model, options are priced using a different day-night volatility ratio than the actual ratio for the underlying price. We simulate day-night option returns from the models under realistic parameter values. Both models produce similar results. The models are able to replicate not only the signs but also the magnitudes of day-night option returns. The fit is particularly good when option prices completely ignore day-night volatility seasonality (i.e., as if per-hour day and night volatilities are equal). Finally, we validate our cross-stock test, as we find comparable regression results in a simulated panel of option returns on the day-night volatility ratio.

Overall, these tests strongly support the volatility bias as a primary explanation for the return asymmetry. However, we want to highlight an important limitation. We can potentially test the bias in the time series of day-night returns for S&P500 index options. However, despite relying on one of the longest intraday option samples, we lack statistical power to study conditional properties of day-night returns for S&P options. Only few variables significantly predict time series of day and night S&P option returns.

We also test other alternative explanations. The maturity bias provides an intuitive way to produce day-night return asymmetry. Perhaps intraday returns are positive because option maturity is not adjusted continuously intraday, and thus option prices at the close are computed with maturity, which is too high. Indeed, under realistic parameter values, the maturity bias produces average day-night option returns that roughly match returns for S&P500 index options. However, this bias implies that average option returns should depend only on maturity and moneyness but not on volatility or underlying price. Thus, the bias does not fit the average day-night returns for *equity* options and the return variation across stocks (e.g., the maturity bias cannot explain stocks, such as IShares China Large-Cap ETF, with positive night returns and negative day option returns). Furthermore, according to this bias, option prices correctly track the U-shaped intraday volatility. Thus, option returns should be equal and positive in all intraday sub-periods. However, equity option returns in the morning and afternoon are higher than at noon. Finally, anecdotal evidence from the VIX CBOE white paper suggests that option practitioners measure time-to-maturity at a minute level. Overall, maturity bias fits some of the facts for S&P index options but is not sufficiently flexible to explain variation in day-night return asymmetry.

Buying pressure may push option prices higher and cause positive intraday returns. We compute option order imbalance in two ways: (i) using open-close data that identifies which side is taken by option market-makers (OMMs) and (ii) from trades that take liquidity by crossing the spread in the regular intraday data (OPRA). These two imbalances seem to capture different types of price pressure, as their correlation is low (12%). Demand pressure is a promising rationale because intraday returns and order imbalances are both positive for S&P options. However, unlike with S&P 500 options, the signs do not match for equity options. Intraday returns are still positive, but order imbalances are negative, as investors mostly write covered calls. Second, option order flow is relatively balanced, and the imbalances may not be sufficient to produce observed returns. Third, demand pressure predicts partial overnight price reversal, but we found (i) zero correlation between day and night returns and (ii) failure of order imbalances to negatively predict night returns. Fourth, none of the coefficients is affected when we add order imbalances to our main test with option returns regressed on day-night volatility ratio. Finally, day-night asymmetry is equally strong for the subsample of stocks, with little option volume and thus little price pressure. Overall, we confirm that order imbalances are some of the strongest return predictors (Muravyev, 2016), but they help little in explaining day-night return asymmetry.

Finally, to account for the discretization bias, we show that our results are robust to alternative delta-hedging strategies and hedging frequency. For example, day and night option returns stay virtually unchanged after controlling for contemporaneous underlying returns. In the baseline case, we delta-hedge five times per day when computing option returns, which is sufficient to minimize bias. Our tests reduce, but do not completely eliminate, this concern.

Overall, multiple explanations likely contribute to the day-night effect, but volatility bias passes most of the tests and is by far the most promising explanation. The remainder of the paper is organized as follows: In Section 2, we briefly review related literature. In Section 3, we describe the data and methodology. Section 4 documents the asymmetry between day and night option returns. Section 5 explains the relationship between volatility and option returns. Sections 6, 7, and 8 study potential explanations. Section 9 concludes the paper. The Appendix provides several additional results and tables.

2 Literature and Contribution

This paper contributes to several strands of literature. First, our results are important for the option returns literature. Second, we contribute to the literature on behavioral finance and investor irrationality. Although options provide leverage (Black, 1975) and lottery-like payoffs (Shefrin and Statman, 1993) that can attract speculators, surprisingly few papers study behavioral factors in derivatives markets. Stein (1989) and Poteshman (2001) show that option-implied volatility underreacts to individual daily changes in instantaneous variance and overreacts to periods of mostly increasing or mostly decreasing daily changes in variance. Han (2008) shows that changes in investor sentiment help explain time variation in the slope of index option smile and risk-neutral skewness. Jones and Shemesh (2016) show that returns for stock options are more negative over weekends than weekdays. Overall, these studies argue that option prices react in the right direction, but not by the right amount, while we find that intraday option return has the “wrong” sign, and we also identify a likely mechanism behind the puzzle. Relatedly, the literature on optimal exercise of equity options concludes that professional investors, such as OMMs, almost always exercise their options optimally, but retail investors occasionally make mistakes, as optimal exercise boundaries are hard to compute. This paper focuses on systematic pricing mistakes rather than occasional mistakes of retail investors. On the other hand, option investors are highly sophisticated, which makes mispricing less likely: institutional investors account for most of option trading volume.[7] Indeed, numerous

[7] Muravyev and Pearson (2017) show that most option trades are executed using sophisticated algorithms not available to retail investors.

studies show that option prices and volume contain information about future unscheduled events (e.g., mergers), stock returns, and volatility.

The idea that volatility seasonality should affect option prices goes back to at least Merton (1973) and French (1984). However, we know only one article, Sheikh and Ronn (1994), that investigates intraday option returns. Using data on 30 stocks for 21 months ending prior to the 1987 crisis (pre-volatility skew period), they find, among other results, that "the adjusted option returns" are more negative overnight than intraday, but the difference is not statistically significant, perhaps because of the small sample. Sheikh and Ronn focus on returns towards the end of the trading day, and do not discuss overnight versus intraday returns, nor do they study index options. They argue that differences between option and equity market returns provide evidence of information-based trading in options. Obviously, the options market has changed substantially since the mid-1980s.[8]

A growing literature examines day-night equity returns.[9] Our result that option prices fail to reflect the day-night volatility can be useful for explaining the equity market day-night puzzles. Volatility is a basic input to many risk measures, such as CAPM betas, and thus may affect required night and day returns. Importantly, despite apparent similarity, the day-night effect in the equity market does not affect our results. First, options are delta-hedged so that their beta is close to zero, and thus option and stock returns are uncorrelated. Controlling for stock/index returns does not affect the option day-night effect. Second, unlike in the equity market, the autocorrelation between day and night returns is essentially zero in options. Finally, the options day-night effect is an order of magnitude larger than its equity market counterpart, which is less than one basis point per day in our sample.

3 Data and Methodology

We obtain stock and options data from Nanex, a firm specializing in high-quality data feeds. The original data come from standard data aggregators: OPRA for options and SIP for equities (e.g., TAQ data also use SIP). The data include intraday quoted bid and

[8] Also, Chan, Chung, and Johnson (1995) show that option volume exhibits a U-shaped intraday pattern similar to stock volume; however, we are the first to examine intraday patterns in option order flow/imbalance.

[9] For example, Lockwood and Linn (1990), and more recently Cooper, Cliff, and Gulen (2008), show that all of the equity risk premium in their sample comes from overnight returns. Lou, Polk, and Skouras (2015) and Bogousslavsky (2016) examine how stock anomalies behave intraday and overnight.

ask prices at one-minute frequency for both options and the underlying equities for the sample period from January 2004 to April 2013. For options, we also observe best bid and offer (BBO) from all option exchanges. Timestamps are synchronized across markets. To reduce dataset size, only option contracts with at least one trade on a given day are included. Still, the compressed data require more than twelve terabytes of storage. When needed, we merge our intraday data with daily stock and option prices from CRSP and OptionMetrics by ticker and date. Delta-hedges are computed using S&P 500 index futures data.

Option order imbalances are computed from option trades and pre-trade best bid and ask quoted prices (BBO). First, the quote rule is applied to trade and NBBO (National Best Bid and Offer) to determine whether a trade is buyer or seller-initiated; if a trade is at the NBBO quote midpoint, we apply the quote rule to the BBO prices from the exchange that reported the trade. Alternatively, we compute order imbalances using the so-called open-close data from the ISE for equity options and CBOE for S&P 500 index options. Garleanu, Pedersen, and Poteshman (2008), Muravyev (2016), Ge, Lin, and Pearson (2016), and Fournier and Jacobs (2015), among others, use and describe these data. For each option and day, the data report how much non-OMMs (firms/customers) bought and sold to open new position or to close an existing one. As options are in zero net supply, we follow the literature and compute non-OMM order imbalance as the number of buys minus the number of sells normalized by the total number of trades.

Let us briefly describe the options market structure. The U.S. options market has a similar structure to the equity market, but with some key distinctions. Equity options are typically cross-listed across many fully-electronic exchanges, and the NBBO rule is enforced. Investors can submit limit or market orders, and market-makers are obliged to provide continuous two-sided quotes. All major brokers provide real-time option prices to their clients similarly to stock information. S&P500 index options are special because one exchange, CBOE, has exclusive rights to trade SPX options, and most SPX option trading is still done manually. OMMs play a key role in the options market structure, as they provide continuous bid and ask quotes that investors trade against.[10] CBOE, the largest

[10] Option market making is highly concentrated. According to Citadel, as of late 2008, Citadel (30% of option volume, specialist in options on 1,655 stock names), Susquehanna (1,152 stock names), Timber Hill (1,124), Citi (554), Goldman Sachs (390), Morgan Stanley (286), and UBS (218) dominated this market.

option exchange, recently stated: "In the listed options market, liquidity is supplied by professional market-makers. Most investor orders are executed against market-maker quotations. Due in part to the dispersion of trading interest across hundreds of options series in a single options class, the majority of individual options series would have no posted liquidity if options market-makers were not present. In short, market-maker liquidity is critical to vibrant option markets." The OCC, the main option clearing house, reports that more than 85% of trades have a market-maker on at least one side in 2013.[11] OMMs use sophisticated computer programs to set prices and respond to customer order flow. Almost always (with an occasional client limit order), option returns that we compute are based on the midpoints generated by these OMMs' computer programs. Johnson, et al. (2016) and Muravyev (2016) provide further details on the option market structure.

Open price is computed as the quote midpoint at 9:40 a.m. Both the equity and options markets open at 9:30 a.m. EST. We skip the first ten minutes of trading because, as Chan, Chung, and Johnson (1995) show, option quotes are sporadic and bid-ask spreads are often wide immediately after the market opens. Closing prices are based on the quote midpoint preceding the close, which is at 4:00 p.m. for equity and 4:15 p.m. for S&P500 options. Options and the underlying market typically close/open at the same time. Our main results are robust to alternative specifications of open and close prices.

We apply standard data filters. In order to compute option return over a given time period, we exclude option contracts for which at the beginning of this period (1) option prices violate no-arbitrage bounds, (2) the bid price is greater or equal to the ask price, (3) the bid price is not available or is below 50 cents, (4) the quoted bid-ask spread is more than 70% of the midpoint, or three dollars, or (5) if option delta cannot be computed. Omitting any one of these filters has little effect on our main results.

Delta-hedged option returns are computed using deltas from the Black-Scholes-Merton model; the hedge is revised five times a day (about every 80 minutes). Figure A.1

[11] Also, during our sample period, CBOE exchange rules require that "Designated Primary Market-Makers (DPMs) are required to provide continuous electronic quotes in at least 90% of the non-adjusted option series of each appointed multiply listed option class and in 100% of the non-adjusted option series of each appointed singly listed option class pursuant to Rule 8.85… "continuous electronic quotes" means 99% of the time that the Market-Maker is required to provide electronic quotes in an appointed class on a trading day pursuant to Rule 1.1(ccc)."
http://www.cboe.com/aboutcboe/government-relations/pdf/bank-capital-october-2017.pdf

in the Appendix confirms that intraday returns are robust to alternative hedging frequencies. Following the literature, we define delta-hedged option dollar profit (P&L) for option contract with price C_t between times $t-1$ and t as

$$P\&L_t = C_t - C_{t-1} - \Delta_{t-1} * (S_t - S_{t-1}) \,, \tag{1}$$

where Δ is option delta and S_t is the underlying price at time t. Option delta-hedged return is then computed as[12]

$$Ret_t = \frac{P\&L_t}{C_{t-1}} \tag{2}$$

Following this definition, intraday (open-to-close) returns are computed as the intraday (open-to-close) dollar P&L for a long option position divided by opening option price. Index futures have low margin costs supporting this definition. For brevity, in the rest of the paper, we refer to average delta-hedged option returns computed using the above equations as simply “option returns.” In untabulated results, we show that other ways to normalize P&L (instead of dividing by option price) do not affect the relative magnitude and signs of day-night option returns.

We first compute day and night returns for each option contract, then average them for each underlying, and finally take an equally-weighted average across stocks (this step is redundant for S&P options). The procedure gives us one intraday and overnight option return per stock and date. With slightly less than ten years of data, we have almost 2300 daily observations. When required, we similarly compute returns for option subsamples, such as OTM index puts.

For robustness, we also examine leverage-adjusted option returns, which helps us compare returns of options with different moneyness. Following the literature, the deleveraged option return for Ret_t is defined as:

$$Ret_t^{DL} = \frac{Ret_t}{\psi_{t-1}}, where\ \psi_{t-1} = \left|\frac{\Delta_{t-1} S_{t-1}}{C_{t-1}}\right|,$$

Ret_t is the delta-hedged option return for time period $[t-1, t]$ defined above. ψ_{t-1} is the deleveraged factor, which is usually well above 5.

Empirical work in option pricing typically relies on the estimation of fully specified parametric models. Option returns are easier to interpret than pricing errors of such models

[12] We study regular option returns instead of excess returns because the daily risk-free rate is negligible compared with option returns, so subtracting it makes little difference.

because returns represent the actual gains or losses to a trading strategy. Also, the day-night effect is hard to extract from implied volatility, and thus option returns provide a more natural way to study them. Several others have also noted the advantages of analyzing average option returns.[13]

4 Day-and-Night Effect in Option Returns

4.1. Average Overnight and Intraday Option Returns

In this section, we explore properties of average overnight and intraday option returns. We decompose daily delta-hedged option returns into day (open-to-close) and night (close-to-open) components. Delta-hedge returns for S&P 500 index options, and to a lesser degree for equity options, are negative on average. In Figure 1, we show that these negative returns are entirely due to the returns from the overnight period, which are -1.0% per day, while intraday returns are positive 0.3%. Our magnitudes for total daily option returns are consistent with the literature (e.g., Coval and Shumway (2001)). Table 1 confirms that day and night returns are both statistically significant (t-statistics of 2.6 and -12.0, respectively). This day-night effect is also observed in equity option returns, but magnitudes are expectedly smaller: a -0.4% per day overnight return versus 0.1% intraday (see Figure 1 and Panel B of Table 1). Statistical significance is higher for equity options (t-statistics of -19.5 and 3.0), as averaging across stocks reduces estimation error. We also find evidence of the day-night effect in VIX futures.[14]

Figure 2 shows that despite high variance, overnight returns are remarkably stable over the entire sample period. In particular, this figure compares cumulative option returns over a three-month rolling window for two trading strategies. The conventional strategy of collecting the option risk premium sells a delta-hedged option portfolio and keeps it for the entire day (collecting both day and night returns); however, the overnight strategy only

[13] See, for example, Coval and Shumway (2001), Bondarenko (2003), Driessen, Maenhout, and Vilkov (2009), Duarte and Jones (2007), Broadie, Chernov, and Johannes (2009), Goyal and Saretto (2009), Bakshi, Madan, and Panayotov (2010), and Muravyev (2016).

[14] In Table A.12 in the Appendix, we show that intraday returns for front-month VIX futures are close to zero (0.01%, statistically insignificant), but overnight returns are significantly negative (-0.15%). As VIX futures are traded around the clock, but are highly illiquid outside of normal trading hours, we use the same open and close times as for index options to compute VIX futures returns. All futures with maturities up to six months have negative overnight returns and slightly positive (or zero) intraday returns. After launching in 2004, the market for VIX futures has grown dramatically only recently, which made futures prices volatile in the beginning of our sample. This may explain the relatively large standard errors.

keeps the short position open overnight and thus has no position intraday. The conventional strategy is highly profitable, but its P&L is volatile, and it loses more than 80% of capital in late 2008. In contrast, the overnight strategy is profitable in every three-month sub-period, including the financial crisis. As a result, it yields more than twice the Sharpe ratio of the conventional strategy. Admittedly, this strategy requires frequent trading and thus is hard to implement in practice. Its average daily profits are smaller than a 6% average effective bid-ask spread in S&P500 options, unless investors avoid paying the entire spread by providing liquidity. Section A.6 in the Appendix discusses how options on SPY ETF, with similar return properties but much smaller transactions costs, can be used to make the strategy potentially profitable after costs. Importantly, high trading costs may explain why the anomaly does not disappear, but not why it exists in the first place.

In Table 3, we confirm that the day-night return asymmetry for S&P500 options is significant in every year of our sample. The smallest day-night difference is 0.89% in 2012. In-line with Figure 2, night returns are consistently negative. The least negative night return is -0.77% in 2008. Intraday returns are positive in some years but are mostly close to zero. They range between -0.21% (t-statistics = -0.8) in 2012 and 1.59% (t-statistic = 2.1) in 2008. We conduct several tests to 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). Obviously, even zero return would be puzzling. 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 spread). 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, Liang, and Liu (2016)), but their option bid-ask spreads are one-half the size of SPX's. Obviously, SPY and SPX returns are extremely correlated. Panel B of Table A.3 in the Appendix shows that average option intraday returns over these three ETFs are positive in eight out of ten years (-0.17% in 2004 and -0.05% in 2012)! Averaging across multiple contracts with lower option bid-ask spread indeed reduces price noise in option returns. Similarly, Panel A of this table 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.

Overall, night returns are consistently negative, but intraday returns are close to zero or mildly positive. Even zero option returns are puzzling because a realistic null hypothesis from a model such as the Heston model, which is a standard way to introduce the variance premium, implies negative option returns in both day and night sub-periods. Under realistic parameter values, the Heston model implies average intraday returns of -0.55% and overnight returns of -0.24%, as reported in Table A.4. The zero return is obviously an upper bound on the average option return in most risk-based models.

Day-night return difference cannot be explained by differences in higher moments of option return distribution. Table 1 shows that day and night option returns have a relatively similar standard deviation of 4.8% and similar 1% and 99% tail quantiles. Thus, in terms of these "naïve" risk measures, day and night returns are similarly risky.[15] [16]

To understand better the nature of intraday returns, we compute average option returns over five equal intraday sub-periods in Table 2. Intraday returns are close to zero in the morning and at noon (-0.02%) and become positive in the afternoon, 0.16% and 0.19% in the last two sub-periods. The non-negative returns in all intraday sub-periods confirm that our results are not driven by some strange price behavior at the open or close. Interestingly, index option returns in the morning do not match the underlying volatility, which is usually U-shaped. However, equity option returns are more positive in the morning (0.10%) and afternoon (0.05%) compared with noon-time (-0.04%), as is shown in Panel B of Table 2, and thus match the U-shaped volatility seasonality. Perhaps we do not have enough statistical power to find the U-shape in S&P option returns. Intraday

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[15] Expectedly, the median return is lower than the mean because an option payoff is non-linear. Median night return is -1.2%, and thus our main result is not driven by outliers. Median intraday return is slightly negative (-0.38%), reflecting the fact that an option straddle (put plus call) has negative return on a median day, as stock price remains unchanged in this median scenario, and thus an option loses time value.

[16] Finally, we compare day and night return distributions for the underlying. Table A.1 reports return distributions for S&P500 index and individual stocks, respectively. Average S&P index returns are close to zero during our sample period: 0.008% for overnight period and -0.004% for intraday. That is, the difference is only one basis point and is not statistically significant. As for the higher moments, the intraday period is only 6.5 hours (regular trading hours), but its total volatility is 1.5 times higher than the longer overnight period. Similarly, return percentiles are more extreme for intraday returns.

volatility seasonality is one-fourth that of day-night seasonality. However, when we look in Table A.3 at ETF options including SPY with less price noise, morning and afternoon option returns are clearly larger than noon returns, consistent with U-shaped volatility.

We conduct many other tests and find that the main result is markedly robust. Sections A.1 and A.2 in the Appendix explain them in detail.[17] In particular, we consider several alternatives for open/close option prices and returns. All of them have little effect on the day-night return magnitudes. First, to address the concern that open and close prices are computed at a particular time (9:40am and 4:00pm), we re-compute them as an average quoted price during the first and last 15 minutes of trading. Second, to address the concern that bid prices can occasionally be set too low and thus bias the midpoint, we compute returns using only ask (or only bid) prices (Table A.11). Third, despite being widely used, the quote midpoints may not represent prices that investors get. Thus, we compute option returns from average trade prices instead of quote midpoints (Panel B of Table A.10) and find stronger day-night return asymmetry. Fourth, hedging in the underlying may produce spurious returns; therefore, we study straddle returns to address this concern (Panel A of Table A.9). In a straddle, a call is delta-hedged with the put option instead of the underlying. Finally, delta hedging may affect option returns, e.g. because option deltas can be biased. In Figure A.1, we show that intraday returns depend little on the delta-hedging frequency. Moreover, we confirm the day-night effect for raw (unhedged) option returns (Panel B of Table A.9).

Day-night option return asymmetry varies substantially across stocks. This important stylized fact helps us distinguish between alternative explanations. We illustrate this point by investigating major exchange-traded funds (ETFs) in Table A.2. The day-night effect varies across ETFs in a systematic way that matches the pattern in day-night underlying volatility. U.S. index, industry, and commodity ETFs have negative night and positive day option returns. However, option returns for international ETFs (e.g., tickers EEM and EFA) and the long-term Treasury bond ETF (ticker TLT) are negative both

[17] We also confirm in Table 3 that negative overnight returns are not driven by weekends. Night returns become slightly less negative, increasing from -1.0% to -0.8% if weekends are excluded. We thus support the finding of Jones and Shemesh (2016) that option returns are more negative over weekends (Friday to Monday). In untabulated results, we also test whether the volatility seasonality bias that we propose can explain the weekend effect, and it does not. Unfortunately, the weekend effect remains a puzzle.

intraday and overnight. Remarkably, the day-night effect flips sign for the China Large-Cap ETF: night returns are positive, and day returns are negative. These "exceptions" encourage us to compare average option returns with the day/night return volatility for these ETFs. For the Chinese ETF, intraday volatility is less than night volatility; for the international equity ETFs and fixed-income ETF, the day and night volatilities are roughly equal. Finally, for U.S. index and industry ETFs, intraday volatility is much higher than night volatility. Overall, the volatility pattern matches the pattern in average option returns!

Next, we show how day-night option returns depend on option parameters. Overall, day-night return asymmetry is observed in almost all option subsamples. Table 1 shows that return asymmetry is more pronounced as option moneyness decreases. E.g., OTM options have highest leverage and thus more extreme returns: 0.27% intraday and -1.74% at night; however, in-the-money options have little leverage/optionality with day and night returns of only 0.07% and -0.22%. Delta-hedged call and put returns are similar because both produce a similar straddle position after delta-hedging. Finally, Panel B of Table 1 confirms these stylized facts for equity options, but the magnitudes are expectedly smaller.

Return asymmetry declines with time-to-expiration; that is, short-term options have more extreme returns. Table A.6 in the Appendix shows that options with less than three weeks to expiration have night and day returns of -2.6% and 0.7%, while returns for long-term options are close to zero. Returns for equity options show a similar pattern. Table 4 double-sorts options based on maturity and moneyness and shows that the day-night effect is more pronounced for short-term and more OTM options. ITM long-term options have both returns close to zero, while short-term OTM options have night returns of -5.3% and day returns of 0.75%. We also explore how delta-hedged index option returns depend on option Greeks. Table A.7 double-sorts options by normalized option Theta and Vega, option price sensitivity to time-to-expiration and volatility, respectively, from the BSM model. Option return asymmetry is decreasing in Theta and increasing in Vega, with the high-Vega low-Theta portfolio having day-night returns of 0.4% and -2%. Day returns are positive, and night returns are negative for all Vega-Theta portfolios.

All moneyness and maturity categories have positive day and negative night returns. Thus, the day-night return asymmetry will be observed for any combination of options with positive weights. For example, call and puts can be combined into a synthetic variance swap, a key portfolio for studying the variance risk premium. Thus, according to this argument, the day-night effect will also be observed for variance swaps.

Most option return variation across maturity and moneyness is due to option leverage. In Table A.5, we report the deleveraged returns for S&P index options by moneyness and time-to-expiration. As expected, return signs are not affected, but magnitudes decrease after deleveraging. Average returns become comparable across time-to-expiration and are weakly decreasing in moneyness. Most results remain statistically significant for both day and night deleveraged returns.

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 from the previous day, 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 6 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.[18]

Finally, we show the day-night option returns asymmetry cannot be explained by S&P 500 index returns and VIX futures returns. Table A.8 estimates a regression of index option returns on VIX futures returns and index returns separately for day and night

[18] We also sort trading days into portfolios based on market volatility, tail risk, option liquidity, interest rates, and investor sentiment. Consistent with visual evidence in Figure 2, Panel A of Table A.13 in the Appendix 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 extremely positive when volatility is high (0.97% per day) or option liquidity is low (0.57% per day). Intraday returns also depend on the two measures of investor sentiment that we use. The returns are 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 Kelly 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.13 shows that systematic tail risk produces little variation in either day or night option returns.

periods. First, delta-hedging works reasonably well, as the coefficient for index returns is zero for intraday period and relatively small for overnight. Second, intraday returns for options and VIX futures are highly correlated with a t-statistic of 17. However, night returns are much less correlated, as the coefficient is lower than for intraday (0.66 versus 0.92), and the t-statistic is “only” 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.

4.2. Intraday Patterns in Option Order Flow

In this section, we study how option investors trade intraday. To our knowledge, we are the first to study option order imbalances over intraday sub-periods. Following the literature, we compute order imbalance as the difference between the number of buyer- and seller-initiated trades divided by the total number of trades; thus, it is between -100% (all trades are sells) and 100% (all trades are buys). Presumably, investors are generally buying put index options and writing covered calls (long stock, short OTM call) in equity options. We confirm that these strategies remain popular; however, the order flow is remarkably balanced. Table 5 shows that average order imbalance for index puts (calls) is 3.2% (0.9%). That is, out of 100 put trades only 51.5 are buyer-initiated, and 48.5 are seller-initiated. Similarly, for equity options, call and put order imbalances are -5.5% and -1.7%, respectively. We later assess whether these imbalances are sufficiently large to produce large price pressure. Note that while both order imbalance and option returns are positive for S&P options, the signs do not match for equity options, as order imbalance is negative.

How do imbalances evolve over a trading day? Although equity option imbalances do not vary much across intraday sub-periods, index option imbalances do. In the morning, investors tend to buy index puts (a 2% imbalance) with zero call imbalance; however, in the afternoon, they start buying more calls and puts. Call imbalance becomes positive (2%), and put imbalance increases to 5%. A 3% increase in put order imbalance from morning to afternoon is potentially consistent with the fact that most positive intraday returns for S&P

options accrue in the afternoon. However, the imbalance and return patterns clearly do not match for equity options.

These order flow results have several implications. First, the results do not support a popular hypothesis in the options literature that option investors trade aggressively in the last minutes around the close. We find similar order imbalances in the last two sub-periods. Second, flat or increasingly positive imbalances are consistent with option investors not being aware of the day-night option return asymmetry. The day-night effect encourages option sellers to execute their trades in the afternoon rather than in the morning. Investors selling options in the morning suffer from positive intraday returns and are not compensated for taking intraday volatility. Contrary to this prediction, option order imbalance is balanced though the day and, if anything, is slightly more positive in the afternoon. That is, investors who take liquidity buy more, instead of selling, options. The brief description of the option market structure in Section 3 explains that most of the bid and ask prices are quoted by option market makers. They provide liquidity that other investors take with market orders. Thus, if option investors do not take advantage of the day-night effect, then liquidity providers (OMMs) do not lose money by posting biased option prices. If posting biased option prices does not have economic consequences for liquidity providers, this may explain why this effect persists. Overall, we document several stylized facts about option order flow and relate them to potential explanations for the day-night effect, especially the price pressure hypothesis that we further discuss in Section 8.2.

5 Volatility and Option Returns

In this section, we explain the basic intuition about option returns and their relationship to the underlying volatility. This relationship is central to the volatility bias explanation. We start with the simplest possible case, the classic BSM model without the variance risk premium (VRP). Most academic research is focused on option prices and implied volatilities, but average option returns are in some ways more intuitive because they correspond to profitability of option trading strategies, and thus classic asset pricing ideas, such as the efficient market hypothesis (EMH) apply. Therefore, according to the EMH, any abnormal average option returns should be compensation for taking risk. Thus, excess option returns (after delta-hedging takes away the equity risk premium) in the BSM model with no VRP must be zero on average, otherwise arbitrageurs quickly eliminate this mispricing. Mathematically, this EMH argument corresponds to the risk neutral pricing, an option price equals to the expected payoff under the risk neutral measure. This simple intuition carries through if volatility is a deterministic function of time, as in Merton (1973). The EMH implies that option prices correctly reflect expected volatility, so (average excess delta-hedged) option returns must be zero.[19]

We use analytical formulas for option returns to convey intuition about return signs, while model simulations are useful for confirming the intuition and getting a sense about return magnitudes. Panel A of Figure 4 nicely illustrates the point about zero option returns in the BSM model with day-night volatility seasonality but without VRP. This simplest possible case may seem trivial, but we find it crucial for conveying the intuition. The figure shows instantaneous volatility, implied volatility, and average day and night option returns for an ATM straddle as a function of time-to-expiration. An option is reset to ATM at the start of each period. The underlying volatility (upper-left panel) follows a step function over time, it is high during the day and low at night (13% vs. 32% p.a.). In this simple setup without VRP, implied volatility equals to the average volatility until option maturity. If the same number of days and nights is left (S&P options expire at the open, so the last period is overnight), implied volatility is constant at 20%. Implied volatility is higher in the morning, as intraday periods outnumber night periods. For a 30-day option, the implied volatility difference between day and night is 20% vs. 20.2%, or 1% in relative terms. The effect is obviously larger for short-maturity options, as one extra intraday period contributes more to average volatility. Most importantly, realized option returns are volatile but are zero on average for both day and night periods. This example has no misperception or volatility bias; option prices fully reflect the underlying volatility. Thinking about option returns in terms of implied volatilities may lead to confusion. Whether options are cheap or expensive is jointly determined by implied and realized volatilities, and option return is a convenient way to access this. Indeed, several papers show analytically that option returns are proportional to the difference between *instantaneous* implied and realized variances. For example, Broadie, Chernov, and Johannes (RFS, 2009, Equations 6 and 7) show that

[19] We also briefly mention the third way of thinking about option returns as a trade-off between the theta (time decay) and the gamma (volatility). The two parts magically offset each other in the Black-Scholes PDE. This approach is popular, but we do not find it useful for our setting, as it tends to create confusion.

for a general Heston model, the delta-hedged excess option return for holding period $[t_1, t_2]$ is the integral of $d\Pi_t$ and divided by option price c_t:

$$OptRet(t_1, t_2) = \frac{1}{c_t} E_t \int_{t_1}^{t_2} d\Pi_t = \frac{1}{c_t} \int_{t_1}^{t_2} \frac{1}{2} \frac{\partial^2 c}{\partial S^2} \left[\sigma^2_{Real(t)} - \sigma^2_{Opt(t)}\right] S_t^2 dt \qquad (3)$$

That is, instantaneous return of a properly delta-hedged option portfolio is proportional to the difference between *instantaneous* realized and implied variances. This difference is then multiplied by option gamma and the squared stock price and is integrated over time. The term $\sigma^2_{Opt(t)}$ reflects option-implied expectations about *instantaneous* volatility. If volatility beliefs are unbiased $\sigma^2_{Real(t)} = \sigma^2_{Opt(t)}$ for any t, option returns are zero on average. Realized option returns, of course, are usually non-zero as realized volatility differs from its average in a given sample.

We extend this intuition to our day-night return puzzle. If option prices understate volatility intraday $\sigma_{Real(t)} > \sigma_{Opt(t)}$, Equation (3) implies option returns will be positive on average. If the reverse is true at night $\sigma_{Real(t)} < \sigma_{Opt(t)}$, returns will be negative. Indeed, imagine that in the BSM model without VRP from in the example of Figure 4, option investors do not realize that day and night volatilities differ ($\sigma_d = 13\%$ vs. $\sigma_n = 32\%$ p.a.) and instead assume constant volatility $\sigma_d^o = \sigma_n^o = 20\%$ p.a. That is, they price total daily variance correctly, but not the split between day and night. Panel B of Figure 4 confirms this intuition: option returns become positive intraday and negative overnight (0.8% and -0.8% for 30-day options). The day and night returns sum to zero because no VRP is in this model.

To confirm this intuition analytically for a more general class of option models, Equation (3) can be re-written for day and night option returns:

$$E(ORet_d) = \frac{1}{c_t} E_t \int_{t_{open}}^{t_{close}} d\Pi_t = \frac{1}{c} \int_{t_{open}}^{t_{close}} \frac{1}{2} \frac{\partial^2 c}{\partial S^2} \{(\sigma_d)^2 - (\sigma_d^o)^2\} S_t^2 dt > 0 \qquad (4)$$

$$E(ORet_n) = \frac{1}{c_t} E_t \int_{t_{close}}^{t_{open}} d\Pi_t = \frac{1}{c_t} \int_{t_{close}}^{t_{open}} \frac{1}{2} \frac{\partial^2 c}{\partial S^2} \{(\sigma_n)^2 - (\sigma_n^o)^2\} S_t^2 dt < 0 \qquad (5)$$

and $\sigma_d > \sigma_d^o$, and $\sigma_n < \sigma_n^o$. These integrals cannot be solved analytically, but the return signs are clear. Thus, volatility misperception or bias is necessary to produce non-zero returns in the no VRP case. If VRP is negative, then negative returns can be a result of biased option prices or compensation for taking volatility risk; positive option returns are harder to reconcile with the risk premium.

6 Challenges for Rational Explanations

So far, we document puzzling empirical facts about option returns, which is our main result. In this section, we discuss why conventional explanations for option returns fail to explain adequately the day-night return asymmetry. We examine a wide range of potential explanations, including risk-based option pricing theories, financial frictions, and behavioral explanations. Although most of these explanations are consistent with some of the facts, almost all of them are unable to replicate positive intraday option returns, and even zero returns would be puzzling. Moreover, the proposed theories should not only explain the day-night return asymmetry but also its cross-asset variation. For most ETFs and stocks, option returns are positive intraday, but for some stocks the pattern is reversed with positive returns overnight. However, a behavioral explanation, the volatility seasonality bias, fits most empirical facts relatively well. After extensively testing the volatility bias, we also test other promising explanations: the discretization bias, the demand pressure, and the maturity bias. Overall, multiple explanations likely contribute to the day-night effect, but the volatility bias is by far the most promising.

In conventional models, negative average option returns compensate investors for taking volatility and jump risks. The intuition is simple. As we explain in Section 5, average delta-hedged option returns are proportional to the difference between realized and implied variances. During "bad" periods, such as financial crisis or stock market crashes, volatility spikes (is higher than its ex-ante expectation), and thus option returns are positive. Option returns are high in bad states of the world, and, thus, according to most risk-based theories, average option returns should be negative. Many theoretical papers formalize this point. For these models to explain day-night return asymmetry, we assume that option investors are averse to night volatility/jumps, but love intraday volatility such that they are willing to accept intraday risk for free, or even pay for it. If these theories are responsible for the day-night effect, this has profound implications about option investors' risk-aversion (i.e., that they are risk seekers). Several of our tests indirectly address this explanation. First, day and night option return distributions are similar (except, of course, for the mean), implying similar risk profiles during day or night periods (Table 1). Second, night returns do not depend on the ex-ante jump measures (Panel B of Table A.13 in the Appendix). Third, the stochastic process for the underlying is not too different across the two sub-periods (Table A.1); indeed, the overnight period has lower stock return variance. Finally, if night returns are risky, then a strategy of selling volatility overnight should occasionally lose money, yet it is profitable in every three-month period (Figure 2).

Peso problem can potentially explain many of asset pricing anomalies. The idea is that a given sample may be unrepresentative because it missed a "rare disaster," e.g., a war, which typically triggers large negative stock returns. Peso problem can potentially explain why night returns are so negative; however, missing a rare disaster would enhance the intraday return puzzle. A disaster triggers extreme stock returns that translate into large positive option returns. Thus, peso problem implies that the "true" average return is even more positive than our estimate. Also, night and day returns should depend on the ex-ante disaster likelihood captured by the tail risk measures, but they do not in the data (Panel B of Table A.13). Finally, peso problem struggles to explain the cross-asset variation in day-night asymmetry. Overall, peso problem is useful for explaining negative option returns over longer horizons, but it inadequately explains the day-night puzzle.

We next consider several financial frictions that are particularly prominent during the overnight period. For one thing, option market-makers (OMMs) cannot adjust their option positions at night because the market is closed. Relatedly, this period is also special because the underlying market is liquid intraday but illiquid at night. Thus, although OMMs can delta-hedge frequently and seamlessly during the day, they cannot adjust their hedges at night.[20] Although return variance is larger intraday, volatility of an option portfolio can be substantially reduced intraday by frequent delta-hedging with index futures. Thus, the night period has more residual volatility and is riskier in this sense. Option investors may require a larger premium to carry positions overnight. This natural theory may explain why night returns are more negative than day returns. Unfortunately, it does not explain the remaining facts. Most importantly, it predicts that intraday returns should also be negative, but less negative than night returns. Second, night returns should be more negative when volatility is high (high VIX), as the overnight risk is proportional

[20] For example, Figlewski (1989) shows that even with frequent delta-hedging, the residual standard deviation that remained unhedged is large. Thus, even small transaction costs make the market incomplete.

to OMM's risk-aversion, position size, and volatility, but night returns depend little on volatility (Table A.13). Finally, as after-hours trading in index futures became more liquid in recent year, adjusting delta-hedges became easier overnight, and thus night returns should be less negative in recent years, but they changed little (Table 3). Overall, OMMs certainly cannot properly hedge overnight and thus are exposed to significant night jump risk. This friction can potentially explain why night returns are more negative, but it fails to explain sufficiently the day-night asymmetry.

The night period is also special because funding and margin costs are usually incurred overnight (and thus are small intraday). These large overnight costs imply that the day-night effect should be more pronounced when interest rates are high. However, night returns are slightly more negative when interest rates are low (Table A.13). Also, such costs imply that intraday option returns should be similarly positive for all securities and thus cannot explain the cross-asset variation in the day-night effect.

Although the S&P 500 index options are some of the most important and actively traded options in the world, their trading costs are high. The effective bid-ask spread is more than 6% on average, and it has decreased little over time. Although we tentatively show in Section A.6 that arbitrageurs with good execution algorithms can potentially make after-costs profits (they, of course, can also provide liquidity with limit orders), selling volatility overnight is not profitable after costs for most investors. Investors can still reduce their trading costs by executing option buys in the morning and sells in the afternoon. Overall, large transaction costs can explain why arbitrageurs do not eliminate the day-night effect, but not why this anomaly exists in the first place.

In summary, many of these theories have implications for negative overnight and long-term option returns, but only few can produce positive intraday returns. We discuss and test them below.

7 Volatility Bias

Given that rational theories have limited success explaining positive intraday returns, we consider behavioral explanations. Even for them, fitting the facts is not easy. We originally hypothesized that option investors may fail to continuously adjust time-to-expiration during a trading day and thus overstate option maturity by almost one day at the close. This maturity bias, which we study in Section 8.1, generates positive intraday and negative night returns but does not match the cross-asset variation of the day-night effect. Luckily, these cross-sectional patterns directed us to the volatility bias explanation.

According to volatility seasonality bias, option prices correctly reflect the total daily stock volatility. However, they get the split between day and night volatilities wrong by ignoring day-night volatility seasonality. The underlying volatility is much higher intraday than at night, which is perhaps the strongest volatility seasonality. Section 5 explains that option returns are proportional to the difference between *instantaneous* realized and implied return variances. Implied volatility is usually set above the expected realized volatility, which leads to negative option returns. The failure to account for volatility seasonality translates into option returns. Positive intraday returns mean that option prices systematically understate intraday volatility, and similarly large negative night returns suggest that night volatility is overstated.

Although the volatility bias fits the main fact--negative night and mildly positive intraday option returns--this is only the first step in validating this explanation. We test the bias in three ways. The first test explores cross-sectional variation in day-night volatility. The second test similarly explores the intraday U-shaped volatility seasonality. The third test confirms the bias prediction that options with shorter maturity have more pronounced day-night return asymmetry, even after returns are adjusted for leverage. We incorporate the bias into popular option pricing models (BSM and Heston) and confirm that it can produce day-night return patterns observed in the data under realistic parameter values. Our main tests are cross-sectional because we lack statistical power for S&P index options to test conditional hypotheses. Overall, these tests convincingly show that the volatility bias is a major contributor to day-night return asymmetry.

Our main test is inspired by the anecdotal evidence in Section 4.1 about option return and volatility variation for international ETFs. The volatility bias implies that stocks with more pronounced day-night volatility seasonality should have higher day-night asymmetry in option returns. Indeed, according to the bias, option prices ignore the fact that day and night volatilities are above and below the overall volatility average (day + night). Thus, the more intraday volatility deviates from the overall average, the more positive intraday option returns are, hence higher return asymmetry. Equations 4 and 5 formalize this logic by relating option returns to volatility.

We measure day-night volatility seasonality by a simple ratio of (per hour) intraday and night volatilities, $\lambda_t^i = \sigma_{day,t}^i / \sigma_{night,t}^i$, where intraday volatility, $\sigma_{day,t}^i$ ($\sigma_{night,t}^i$), is computed as the standard deviation of open-to-close (close-to-open) underlying returns over previous 60 days. Section A.3 explores day-night seasonality over our sample period. In short, the average volatility ratio for S&P500 index is 2.5, and it is relatively stable over our sample period (Figure 3). An average stock has a volatility ratio of 3.2. The 90% and 10% quantiles of the cross-sectional distribution are 4.6 and 1.7 (Figure A.2). The ratio is quite consistent, and stocks with high day-night volatility seasonality continue to have high future seasonality.

We apply the proposed test to the cross-section of optionable stocks. With more than a thousand stocks on a typical day and significant variation in the volatility ratio, this approach provides sufficient statistical power.[21] Similar to the cross-section of stock return tests, we use portfolio sorts and Fama-MacBeth regressions. The portfolio test sorts stocks into five portfolios based on their historical day-night volatility ratio, and then computes average day and night option returns over all stocks in a portfolio. As Table 8 shows, day-night volatility seasonality varies from 1.6 to 4.9 between bottom and top quintiles; we exploit this significant variation. As predicted by the bias, as the day-night volatility ratio increases, night returns decrease from -0.33% to -0.52%, and intraday returns increase from -0.03% to 0.26%. The difference between high and low portfolios is highly significant with t-statistics of -11 and 18. Thus, the day-night option return spread more than doubles from -0.30% to -0.78%, as the volatility ratio increases from 1.6 to 4.9, an almost identical relative change (2.6 times versus 3.0). These portfolio sorts support the volatility bias.

Portfolio sorts are more intuitive, but Fama-MacBeth regressions let us control for other factors affecting option returns. As reported in Table 7, we estimate separate regressions for day and night returns on the day-night volatility ratio and controls. The approach and interpretation are similar to the cross-section of stock returns tests. In the intercept-only regression, intercepts are equal to the average day and night option returns, 0.1% and -0.4%. We try to explain these abnormal returns by adding explanatory variables. Adding the volatility ratio to the intercept-only regressions produces two notable results:

[21] We can also potentially apply the test to the time-series of S&P option returns. However, time-variation in average returns and volatility is hard to reliably estimate, as discussed in Section 4.

(i) the ratio has the correct signs and is highly significant, and (ii) the intercepts in the day and night regressions become similarly negative. The volatility ratio coefficient is positive (0.11) in the intraday regression. That is, the higher day-night volatility ratio corresponds to more positive intraday option returns as predicted by the bias. Similarly, the ratio has a negative coefficient of -0.09 in the night regression. Night returns are more negative if the volatility ratio is high. Both results are statistically significant with t-statistics of 15.1 and -11.6. Interestingly, the coefficients match in magnitude but differ in sign ($0.11 \cong |-0.09|$). We show in simulations below that this pattern is consistent with the volatility bias if option prices completely ignore the day-night volatility seasonality. Second, the intercepts change from (0.1%, -0.4%) to (-0.17%, -0.25%) after controlling for the volatility ratio. Thus, after accounting for day-night volatility seasonality, abnormal option returns in the day and night sub-periods are similarly negative. We leave for future research to explore whether OMMs charge additional return premium for overnight risks after controlling for the volatility bias. Finally, all these results hold after adding control variables in the last two columns of Table 7. Furthermore, to test for the demand pressure explanation, we conduct this cross-stock test for a subsample of stocks with little option trading in Section 8.2. The results are almost identical to the full-sample results. We interpret them as evidence that day-night asymmetry is not caused by option illiquidity or by option trading activity.

Overall, this cross-sectional test strongly supports the volatility bias explanation. Specifically, day-night volatility ratio negatively (positively) predicts subsequent night (intraday) option returns across stocks, as implied by the bias. Importantly, this cross-sectional test is robust to biases in volatility estimation. The portfolio sorts are immune to monotonic transformation of the volatility ratio. The assumption is that our volatility ratio proxy is positively correlated with the true volatility ratio.

We use intraday relationship between option returns and volatility to further test the volatility bias. We first compare their averages across intraday sub-periods, and then conduct a similar cross-sectional test based on intraday option returns and volatility seasonality instead of day-night seasonality. Intraday volatility is usually U-shaped. Indeed, Table 9 Panel B shows that volatility is 78% higher in the morning and 20% in the afternoon compared with the noon time. Intraday seasonality is smaller than the day-night seasonality, but a large stock panel gives enough statistical power. In fact, this setup allows us to distinguish between volatility bias and the other behavioral explanation: maturity bias. Although for both these biases option prices misestimate the total variance until option expiration $\sigma^2 * (T-t)$, the maturity bias focuses on the $(T-t)$ part and the volatility bias on σ. The biases have district predictions about how option returns should evolve over a trading day. According to the maturity bias, option prices correctly track/reflect the U-shaped intraday volatility. Thus, option returns should be similarly positive (same magnitude) in all intraday sub-periods. The volatility bias assumes that volatility is constant throughout the day, and thus option returns follow the same U-shaped pattern as volatility and are more positive in the morning and afternoon. We confirm this intuition in the BSM model with both biases.

Consistent with the volatility bias, average option returns have a significant U-shaped seasonality intraday for stocks and most liquid index ETFs. Indeed, for equity options, morning, noon, and afternoon returns are 0.14%, -0.04%, and 0.06%, respectively (Table 9 Panel A). All of these ratios are statistically significant with t-statistics of 6.9, -3.6, and 3.9. We find similar results for the most liquid index ETFs: S&P 500 (SPY), NASDAQ 100 (QQQ), and Russell 2000 (IWM) in Table A.3 Panel B. These ETF are highly correlated with the S&P 500 index but have less noise in option returns owing to lower bid-ask spreads and averaging across multiple ETFs. As discussed in Section 4.1, intraday option returns for S&P index match the right part but not the left part of the U-shaped volatility seasonality. That is, afternoon returns are higher than noon, but morning and noon returns are close to zero (Table 2 Panel A). We lack statistical power for the S&P 500 index. Indeed, intraday volatility seasonality is smaller. For the S&P 500 index, (per-hour) night volatility is 280% higher than intraday, while morning and afternoon volatilities are only 60% higher than mid-day. Also, intraday sub-periods are obviously shorter than day/night periods, leading to smaller option return differences that require a larger sample to detect them. Overall, the intraday seasonality in option returns is more consistent with the volatility bias than with the maturity bias.

Next, we introduce a cross-sectional test based on intraday volatility seasonality, which is similar to the day-night test. According to the volatility bias, stocks with more pronounced U-shaped intraday volatility (noon volatility is much lower than in the morning/afternoon) have a stronger U-shaped pattern in intraday option returns. We indeed find this relationship in Fama-MacBeth regressions of option returns in the morning, midday, afternoon, and their difference on the volatility ratio across these sub-periods. The results reported in Table 9 Panel C are similar to the day-night test. The historical ratio of afternoon-to-noon volatility positively predicts option returns in the afternoon (t-statistic = -2.5) and negatively at noon (t-statistic = 6.5). Thus, the coefficient signs match the bias predictions. The intercepts in these regressions correspond to unexplained average option returns and become insignificant after including the volatility ratio (e.g., morning intercept changes from 0.139% to -0.017%). We find similar results confirming the bias predictions for the morning-to-noon volatility ratio. The results are robust when controlling for other predictors of option returns. Overall, the intraday volatility ratio explains the cross-stock variation in option return during a trading day.

The last test is built on the idea that according to the volatility bias, the day-night effect is stronger for short-term than for long-term options, even after accounting for embedded leverage. We confirm this idea in simulations from the BSM model. Most of the difference in leverage-adjusted day-night returns is between short-term (4-15 days to expiration) and mid-term (16-53 days) options, while the difference between longer-term options is economically small. We test these predictions for S&P 500 option returns. Table 10 shows that the difference is significant for night returns (t-statistic = 5). The intraday return difference has the correct sign but is not statistically significant, perhaps because intraday returns are noisy. We apply the same test to equity option returns, and consistent with test predictions, find highly significant differences in leverage-adjusted day and night returns. The test results are mostly consistent with the volatility bias.

Can the bias produce return magnitudes observed in the data? To study this question, we incorporate day-night volatility seasonality into the BSM and Heston models. In the model, we control by how much option prices underreact to the volatility seasonality. Model details can be found in Sections A.4 and A.5 in the Appendix. Model parameters (Table A.15) are set to match historical data, including negative daily option returns and Broadie et al. (2007). Two key parameters are the actual and perceived (option-implied) day-night volatility ratios; the former governs the underlying volatility, and option prices are computed assuming the latter. In terms of Equations (4) and (5), the true volatility ratio is $\lambda = \sigma_d \ / \sigma_n$, and the option-implied ratio is $\lambda^{IV} = \sigma_d^O / \sigma_n^O$. Section 5 explains two simple examples of the BSM model (without VRP) with and without volatility bias. Figure 4 shows that if options are priced using the correct ratio $\lambda = \lambda^{IV}$, day- and night-option returns are zero (Panel A). However, if option prices underreact to volatility seasonality $\lambda > \lambda^{IV}$, then positive day and negative night returns emerge (Panel B). We study the model for three volatility ratio values: λ = 2.5 is the average day-night ratio for the S&P500 index, and 1.6 and 3.3 capture the ratio range over our sample period in Figure 3. Option-implied beliefs about the volatility ratio λ^{IV} take the same values (1.6, 2.5, or 3.3) and also $\lambda^{IV} = 1$, which assumes the same (per hour) day and night volatility. Importantly, the choice of (λ^{IV}, λ) affects the split between intraday and night volatilities but not the daily total, which is -0.7% per day to match the data.

The models are able to replicate day-night return magnitudes in the data if option prices completely ignore the day-night volatility seasonality. Both models produce similar results, so we only discuss the Heston model as a more natural way to introduce VRP (see Figure A.3 for the BSM results). Figure 5 shows how average day and night option returns depend on (λ^{IV}, λ). Consider $\lambda = \sigma_d / \sigma_n = 2.5$ (upper-right panel), the average day-night volatility ratio in the data. If option prices correctly reflect the ratio $\lambda^{IV} = \lambda$, then both day and night option returns are negative -0.55% and -0.24%. As the option-implied volatility ratio λ^{IV} decreases, and thus option prices start underreacting to the volatility seasonality, asymmetry between day-night option returns increases. E.g., day and night returns are -0.23% and -0.50% for $\lambda^{IV} = 1.6$. In the extreme case, option prices completely ignore day-night volatility seasonality ($\lambda^{IV} = 1$), intraday returns become positive 0.42%, and night returns are -1.05%. These simulated returns are remarkably close to the option returns observed in the data: -1.04% and 0.28% in Table 1! The return pattern is similar for other plausible volatility ratios values λ. Returns are generally negative, but intraday returns become slightly positive for they ignore the seasonality case, ranging from 0.16% for $\lambda = 1.6$ to 0.57% for $\lambda = 3.3$.

Furthermore, we confirm our main cross-sectional test as we find similar regression results in a simulated panel of option returns from the BSM model (Heston model is too computationally expensive). We simulate a panel of option returns for a cross-section of one hundred stocks, each with its own volatility ratio, λ. We assume the full volatility bias case $\lambda^{IV} = 1$ and uniformly draw λ from between 1.5 and 5, which matches the range in the data in Figure A.2. Table 11 reports the Fama-MacBeth cross-sectional regressions for simulated data. We find the same patterns as in the regressions for the actual data in Table 7. In particular, stocks with higher day-night volatility seasonality have more pronounced day-night option return asymmetry. The coefficients for the volatility ratio λ in the day and night regressions have the same magnitude but opposite sign, $\beta^{\lambda}_{\mathrm{day}} = 0.08$ and $\beta^{\lambda}_{\mathrm{night}} = -0.08$. Finally, also matching the data, both day and night intercepts become negative after controlling for the volatility ratio.

Assuming realistic parameters, these models produce not only the signs but also the magnitudes of the day-night option returns. This calibration exercise also implies that option prices do not simply underreact but seem to completely ignore the day-night volatility seasonality. Furthermore, we confirm the results for the cross-stock test as we find similar regression results in a simulated panel of option returns.

Overall, we conduct numerous tests to validate the volatility bias. These tests with few exceptions strongly support this explanation for the day-night return asymmetry.

8 Other Promising Explanations

In this section, we explore three other promising explanations: the maturity bias, the demand pressure, and the discretization bias.

8.1. Maturity Bias

The maturity bias is another behavioral explanation: perhaps option investors only adjust time-to-maturity at the open instead of continuously changing it throughout the day. That is, a 30-day option is assumed to remain exactly 30-days during the entire trading day and becomes 29-days only at the next-day open. As option prices are increasing in time-to-expiration, this bias makes closing prices too high, and thus option returns are more negative at night and positive intraday. The bias is intuitive and plausible. What if most option investors use the same software that contains the maturity bias?

The maturity bias does not affect total daily option returns, but only the return split between day and night. Indeed, options would be priced with correct maturity at the open and mispriced during the rest of the day. We first use simulations to assess whether the bias can produce significant option returns. We consider a simple BSM model without VRP, so that average option returns are zero. Under realistic parameter values used in other simulations above, average intraday and night returns are 0.57% and -0.58%, respectively, as reported in Panel A of Table 13. The bias produces a sizable difference between day and night returns. Next, we add realistic VRP in the Heston model similar to the alternative null hypothesis in Table A.4. In the Heston model, day and night returns decrease to 0.02% and -0.82%. Thus, the spread between the day and night returns under the maturity bias is 0.84% and is roughly comparable to the 1.32% return spread for the S&P index options in Table 1. Overall, these simulations confirm that the maturity bias can generate a sufficiently large day-night return asymmetry for S&P 500 options.

We next explore how the returns produced by this bias depend on volatility and option parameters. In panel B of Table 13, we report average intraday option returns by maturity and moneyness for two stock volatility levels: σ=15% and σ=30% in the BSM model with the maturity bias. Surprisingly, under the maturity bias, option returns across moneyness and maturity brackets do not respond to the two-fold increase in volatility. We also tried other volatility levels and parameter values. As expected, returns do depend on maturity and moneyness, with higher embedded leverage options having more pronounced day-night return asymmetry.

Can the maturity bias explain the cross-stock variation of the day-night effect? The bias has strong predictions. First, by construction, option returns should always be more positive intraday than overnight. Thus, the bias cannot explain why some stocks, such as IShares China Large-Cap ETF, have persistently positive night returns and negative intraday returns. Second, the returns do not depend on volatility and thus should vary little across stocks (all the variation is due to variation in VRP and average moneyness and maturity). However, we find that day-night return asymmetry varies across stocks with the day-night volatility ratio. In short, the maturity bias fails to explain adequately the cross-asset variation in day-night option returns.

We already discussed our intraday volatility test in Section 7. According to the maturity bias, option prices correctly track/reflect the U-shaped intraday volatility seasonality. Thus, option returns should be similarly positive in all intraday sub-periods. The simulations from a BSM model with the maturity bias confirm this intuition. Consistent with predictions of the volatility bias and contrary to the maturity bias, we find a clear U-shaped return pattern in the panel of equity option returns. Indeed, Panel A of Table 9 shows that option returns are much lower mid-day than in the morning or afternoon: -0.04% versus 0.14% and 0.06%, respectively. The difference is both economically and statistically significant with t-statistics greater than 7.

Finally, we provide anecdotal evidence that practitioners compute time-to-expiration at a minute level. CBOE (2009), the VIX white paper that describes how CBOE computes VIX index, says on page 5 that "the VIX calculation measures time to expiration, T, in calendar days and divides each day into minutes in order to replicate the precision that is commonly used by professional option and volatility traders." On the other hand, VIX methodology does not address the day-night or other seasonal volatility patterns; thus, VIX is mechanically higher at the open and lower at the close of the market.

Overall, the maturity bias is difficult to test because it implies little cross-sectional return variation: all stocks should have option returns about 0.5% higher intraday and 0.5% lower at night relative to the no-bias case. The bias can generate a sizable day-night return difference, but does not explain the cross-asset variation in the day-night effect.

8.2. Demand pressure

We explore and test the demand pressure hypothesis. This hypothesis is easier to test than the maturity bias because order flow is directly observed and varies across stocks. Overall, we find that demand pressure is a good predictor of current and future option returns, yet it does little for explaining *average* day and night returns.

Our paper is the first to compare option order imbalances using both open-close and intraday OPRA data. Order imbalances computed from tick level OPRA data (intraday imbalances) can be affected by estimation error. Therefore, we also compute order imbalances from the open-close data, used by Garleanu, et al. (2009), among others. The ISE and CBOE open-close data identify non-market-maker order flow at the daily frequency and without estimation error. Note that for S&P 500 options, open-close data cover all trading volume because these options trade exclusively at CBOE, while for equity options, the ISE open-close data only cover trading volume at ISE.

Several interesting facts emerge from comparing the two types of order imbalances. First, average open-close and intraday order imbalances are consistent. Second, option order flow is mostly balanced: buy and sell volumes are comparable. Table A.16 in the

Appendix shows that average open-close versus intraday imbalances are 1.4% and 2.4% for S&P options (owing chiefly to put buying) and are -1.1% and -2.7% for equity options (mostly from call writing). Thus, order flow is relatively balanced, as a 2% imbalance means that 51 options are bought for every 48 options sold. Both average imbalances are relatively small and stable over our sample period. Table A.3 shows that open-close imbalances are positive for S&P options and negative for equity options in every year, including the financial crisis. Intraday imbalances are expectedly noisier, perhaps due to estimation error, than open-close imbalances with a standard deviation of 3.6% versus 5.5%. Third, the correlation between intraday and open-close imbalances is surprisingly low: approximately 12% for S&P index options and 25% for equity options in Table A.16. Perhaps the two order imbalances capture different types of price pressure. Open-close data reflect liquidity demand by non-market-makers, while intraday data reflect direct price pressure from market orders. Of course, OMMs sometimes cross the spread and demand liquidity, which contribute to the difference. Interestingly, put and call imbalances are only weakly correlated. Perhaps investors use calls and puts independently. Overall, we document several novel facts about order imbalances and demand pressure that contribute to the options liquidity literature.

How can demand pressure produce the day-night return effect? Perhaps intraday returns are positive due to unexpectedly positive imbalances that push prices higher. That is, securities with positive (negative) average imbalances should have positive (negative) average intraday option returns. Positive price pressure makes night returns more negative because positive returns due to price pressure partially revert overnight. Also, the price reversion should lead to negative correlation between intraday and night option returns. We test these predictions.

We conduct several tests to improve understanding of the relationship between demand pressure and option returns. First, we propose demand pressure as a potential explanation because intraday returns are positive for S&P options (the big puzzle, 0.3%) and so are option order imbalances (1.4%). However, the signs match for S&P 500 options, but not for equity options. For equity options, intraday returns in Table 1 Panel B are still positive (0.1%), but order imbalances in Table A.16 are negative (-1.1%), as investors write covered calls. The maturity bias fails to explain negative intraday option returns for a subset of stocks, and demand pressure struggles to explain positive returns for an average stock. Second, option order flow is relatively balanced, and the imbalances do not seem large enough to produce observed returns. Keep in mind that under realistic null hypothesis, option intraday returns should not simply be zero but negative and that anticipated (average) imbalances should be reflected in option prices and returns in advance.

Third, we study a subsample of stocks with little option trading volume. The subsample includes 30% of optionable stocks with the least option trading volume during the previous six months. These stocks have average daily option volume of less than $10,000, which is small compared with liquidity-provider capital. In this sample, price pressure is small by construction. If demand pressure is the main explanation, we should not find existence of day-night return asymmetry. However, return asymmetry is as strong here as in the main sample. Table A.14 reports that average day- night returns are 0.16% and -0.62%, a slightly larger asymmetry than for the full sample (0.1% and -0.4%). When we include the day-night volatility ratio, the results are virtually identical to the cross-sectional test on the full sample in Table 7. Intercepts for day and night returns become -0.23% and -0.30% versus -0.17% and -0.25% for the full sample. And the coefficient for the day-night volatility ratio is 0.13 for the day and -0.10 for the night regressions versus 0.11 and -0.09 for the full sample. Overall, the day-night asymmetry is large even for stocks with insignificant option volume and price pressure.

Finally, we test the price reversal predictions of demand pressure. The literature often associates demand pressure with subsequent price reversals. Contrary to this prediction, we find zero correlation between intraday and night returns. The second prediction is that buying pressure during the day pushes prices higher and then prices partially reverse overnight. I.e., order imbalances should negatively predict returns the next night. Table 12 reports how current and lagged order imbalances predict day and night option returns. Consistent with a zero-return correlation, open-close imbalances are uncorrelated with night returns, but intraday imbalances have a positive “wrong” sign. We also confirm the results of Muravyev (2016) that order imbalances strongly predict daily option returns. Indeed, both open-close and intraday order imbalances positively predict intraday option returns. This is not surprising, as Muravyev (2016) argues that imbalances are persistent, and buying pressure today is likely to continue the next day. The cross-sectional test for the volatility bias can be used here. In this test, day and night returns are regressed on an intercept and explanatory variables. Intercept-only regressions reflect average day and night option returns. Including the day-night volatility ratio makes day and night intercepts negative. When we further include order imbalances, intercepts remain the same. That is, order imbalances do not add much to explaining the day-night return asymmetry after controlling for the volatility ratio.

Overall, demand pressure is certainly an important predictor of option returns, but it has limited success in explaining day-night return asymmetry. Nevertheless, our results enhance understanding demand pressure and thus contribute to option liquidity literature.

8.3. Discretization Bias and Robustness

Branger and Schlag (2008) formalize several concerns about option returns that are relevant for our results. First, they argue that option pricing models, and thus option deltas, are often misspecified. Even practitioners cannot agree on whether deltas should be greater or smaller than deltas from the BSM model. Thus, delta-hedged option portfolios may have residual delta exposure. If this residual delta is positive and the positive equity risk premium exceeds the negative variance premium, then average intraday option returns can be positive. Branger and Schlag also introduce the discretization bias. Surprisingly, the average delta-hedged returns are slightly positive, even in the BSM model with unbiased deltas. They show that the discretization error in option returns is high when the equity risk premium and option gamma are high and delta-hedging frequency is low. We conduct several tests to explore the implications of these two hypotheses. First, both day and night option returns stay virtually unchanged after controlling for contemporaneous underlying returns in Table A.8. This regression is akin to accounting for empirical deltas and eliminates any obvious delta biases. Second, average intraday returns depend little on delta-hedging frequency in Figure A.1. More frequent delta-hedging decreases the discretization error. If this error causes positive intraday returns, then the returns should be sensitive to the hedging frequency. Third, Branger and Schlag use extreme parameter values, such as the equity premium of 20%, volatility of 4%, and weekly delta-hedging. We simulate the BSM model with parameters that match our data and find that discretization error is small. Fourth, the discretization error would make both day and night returns more positive. Thus, this error alone cannot explain the return asymmetry, so something else makes night returns so negative. Finally, we further address concerns about delta-hedging by confirming our main result for straddle and raw option returns in Table A.14. Despite all of these tests, we cannot fully eliminate the possibility that a non-linear interaction of these factors leads to the observed return pattern.

A related concern is that the day-night effect is somehow mechanical. Following the literature, we compute option returns from the quote midpoints. We show that the size of the day-night effect does not depend on the option bid-ask spread in Table A.13 and alternative return specifications such as computing returns from only bid or only ask prices in Table A.11. We also compute returns using trade prices instead of the quote midpoints in Table A.10.

9 Conclusion

In this paper, we document a striking pattern in average delta-hedged option returns. The returns are negative overnight but positive intraday. This result is robust across methodological options and observed in different subsamples. We consider a number of potential explanations, but most fail to explain adequately the presence of positive intraday returns and the variation of the day-night option returns across stocks. Obviously, transaction costs affect why the effect is not arbitraged away; they cannot clarify, though, why the anomaly exists in the first place. The discretization bias, maturity bias, and price pressure potentially contribute to day-night return asymmetry. However, day-night volatility bias is the most promising explanation. Perhaps option returns are positive intraday because option traders ignore a well-known fact: stock volatility is much higher intraday than overnight. The volatility bias fits most of the patterns in the data well and is supported by several tests. Study results improve our understanding of price formation in the options market but pose new challenges. If option prices are indeed biased as the volatility bias implies, what does it mean? Volatility is a major input to option pricing models, and these models can be easily adjusted to account for volatility seasonality. We leave for future research exploration of whether other kinds of volatility seasonality are properly reflected in option prices.

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Figure 1 Day and night average option returns

Overnight (close-to-open) and intraday (open-to-close) average delta-hedged returns for S&P 500 index options (Panel A) and equity options (Panel B). Returns are in percentage points per day; (e.g., a -1.04% daily return for overnight index options). We also report 95% confidence intervals. Table 1 complements this figure.

Panel A S&P 500 index option returns

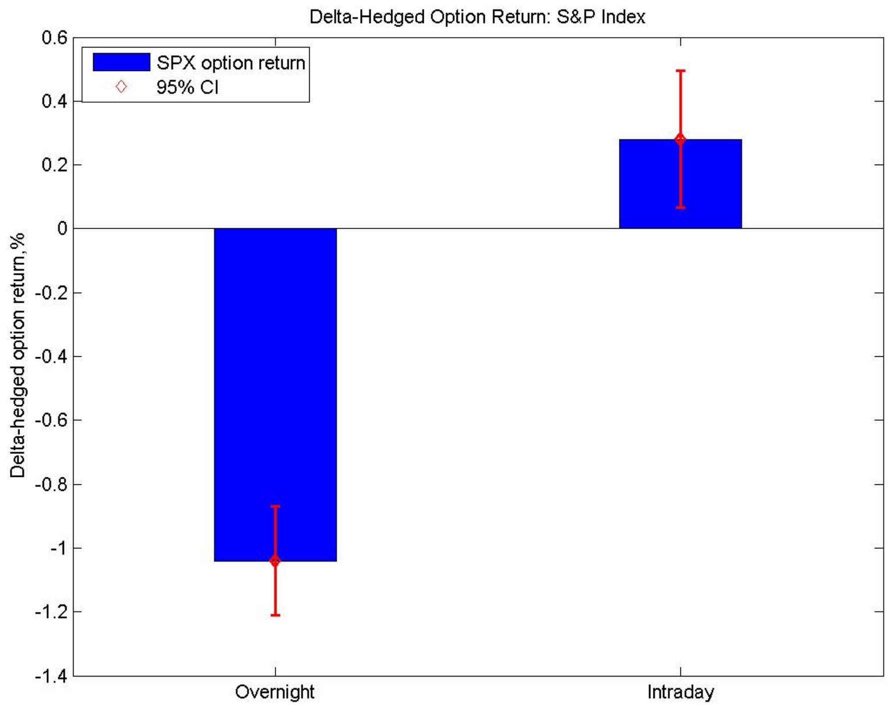

Figure 1 Panel B: Equity option returns

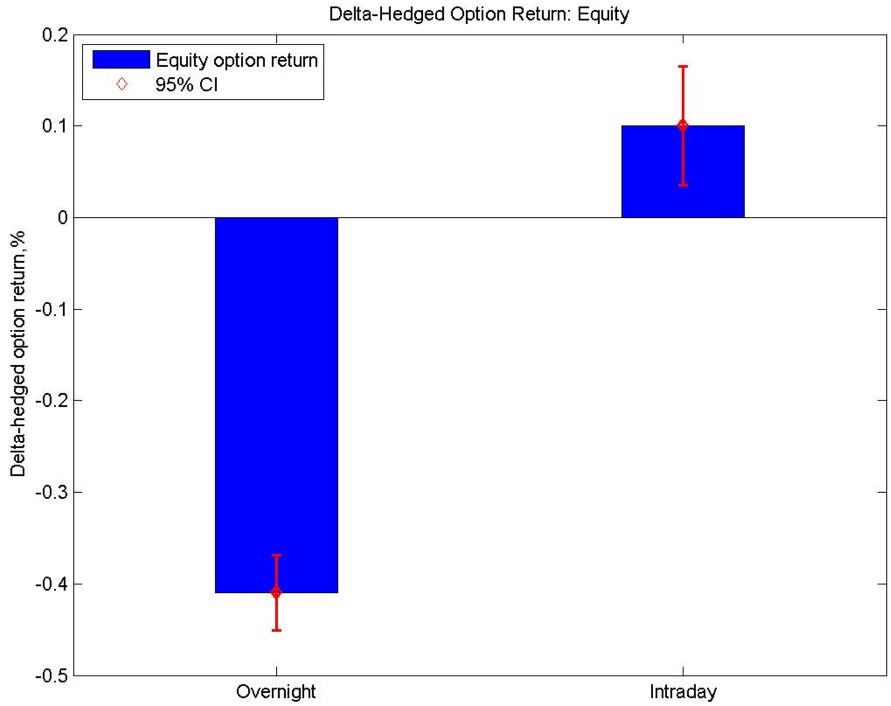

Figure 2 Profitability of two strategies that sell option volatility

Three-month rolling cumulative returns for two trading strategies that sell S&P500 index volatility (i.e., sell delta-hedged options). The conventional strategy keeps a position for the entire day (thin-dashed-grey line), while the proposed strategy sells volatility only during the overnight period (thick-solid-orange line). An investor sells calls and puts that trade at least once on a given day and then delta-hedges the position in the index futures market. Typical returns of these strategies are 30% per three months before transaction costs. Option returns are computed using quote midpoints.

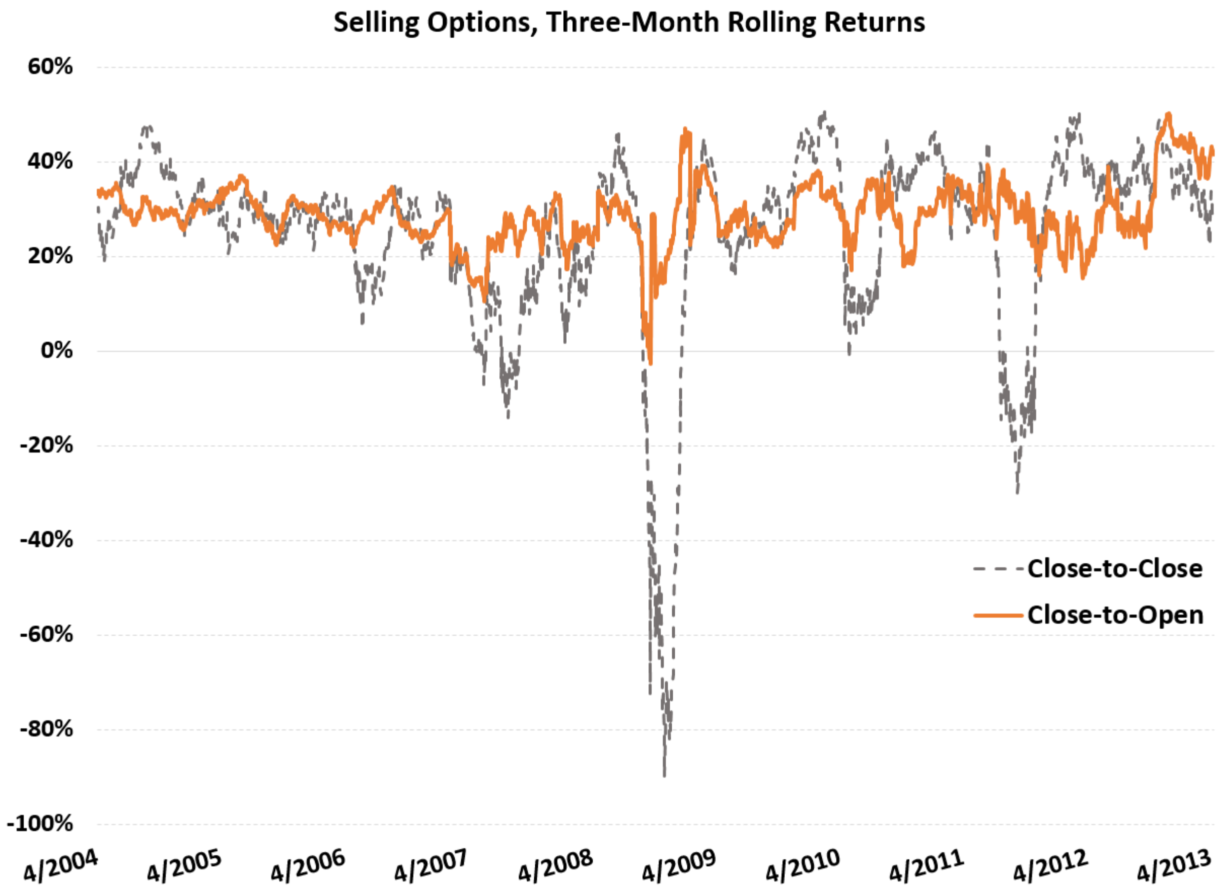

Figure 3 Day and night volatility for S&P 500 index

The top panel shows overnight (close-to-open, green solid line) and intraday (open-to-close, red dashed line) volatility over our sample period. Overnight (intraday) volatility is computed as an average of a 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 a per-day basis (24h) for comparability. The bottom panel plots the ratio of the two volatilities and its 90-day moving average. Figure A.2 in the appendix documents similar results for individual stocks.

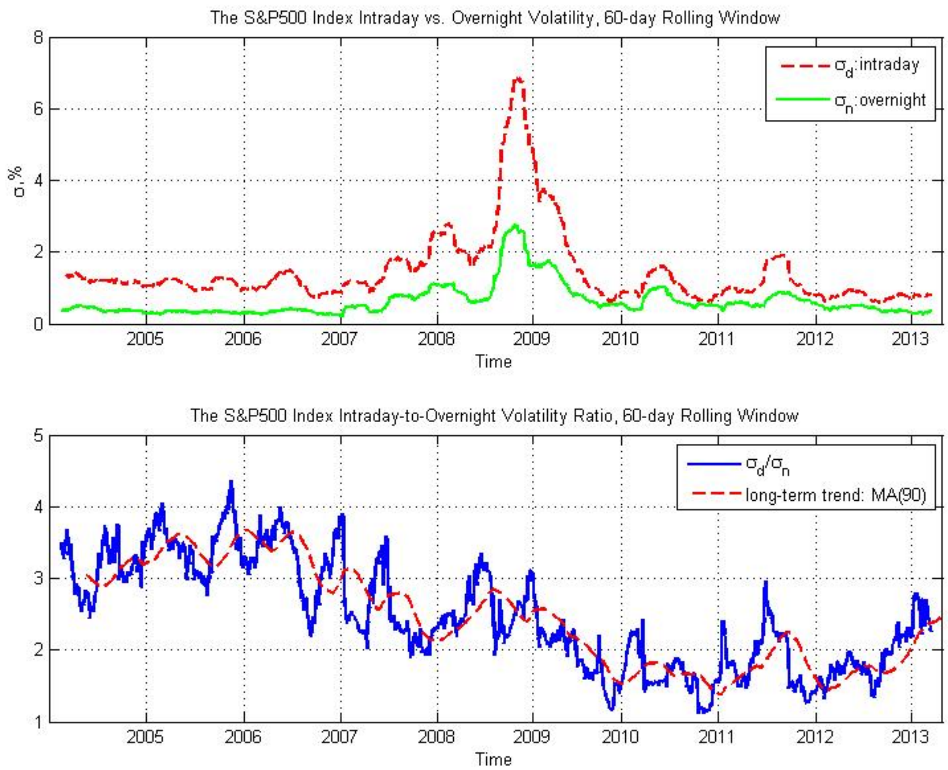

Figure 4 Panel A
The Black-Scholes-Merton model with option prices correctly reflecting day-night volatility seasonality

We compute returns for at-the-money straddles of different maturity (6 to 30 trading days) in a simple Black-Scholes-Merton model with day-night volatility seasonality. The straddle is set to ATM at the beginning of each day and thus is approximately delta-neutral. The BSM model is standard except the instantaneous volatility for the underlying alternates between being high during the day and low during the night, as reported in the upper-left subplot. Both volatilities are scaled to per-unit-of-time and then annualized. The upper-right subplot reports the corresponding implied volatility, which equals to, the average expected volatility until option expiration. For example, implied volatility is higher at the open ("Intraday:beginning"), as high-volatility intraday periods to maturity outnumber low-volatility night periods by one. The bottom left and right subplots report average overnight and intraday excess returns for ATM straddles, respectively. Note that upper- and lower-grid points are -0.5% and 0.5%. Both day and night option returns are close to zero.

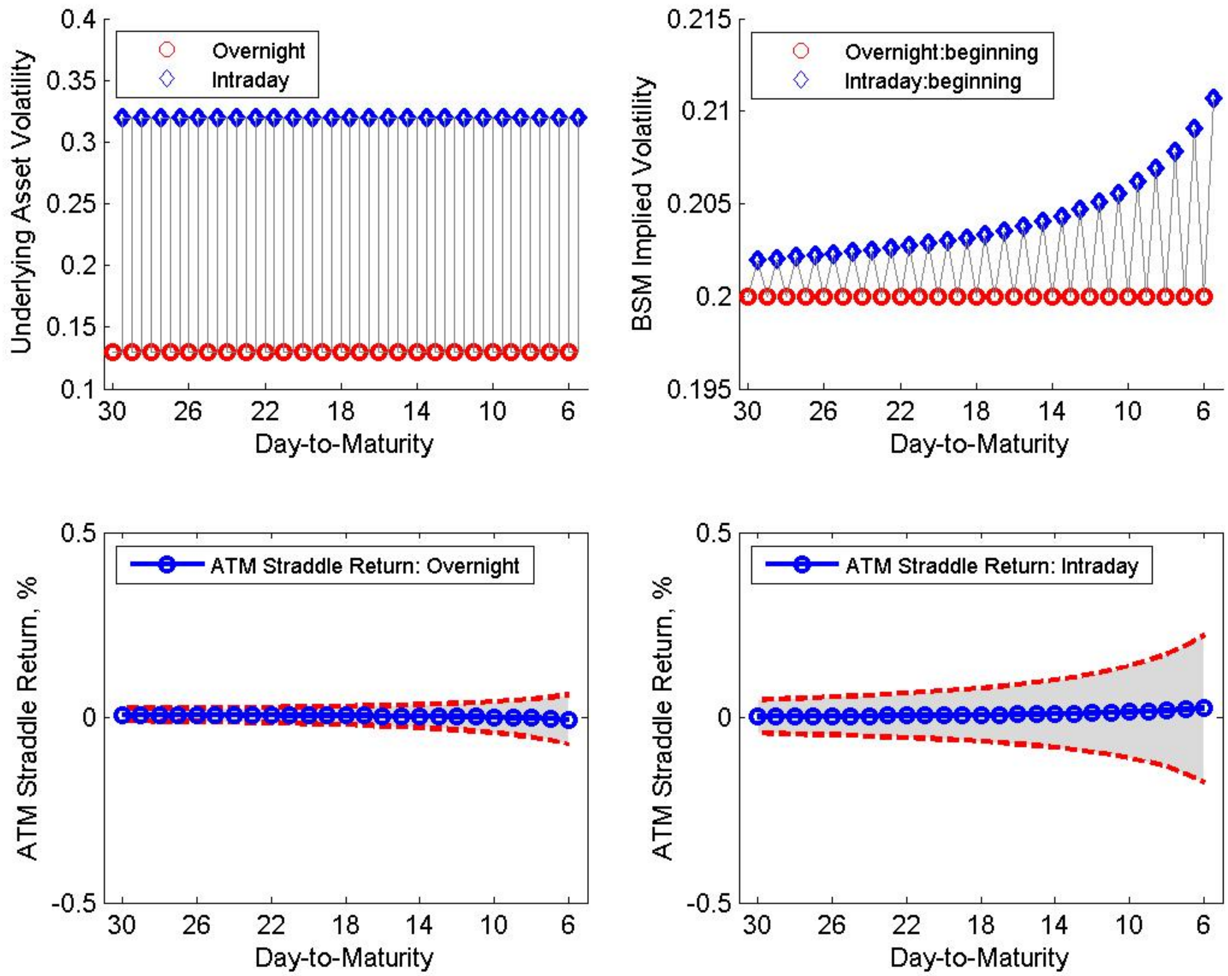

Figure 4 Panel B

The Black-Sholes-Merton model with option prices ignoring day-night volatility seasonality

Similar to Panel A, we compute returns for at-the-money straddles of different maturity (from 6 to 30 trading days) in a simple Black-Scholes-Merton model with day-night seasonality. The only difference with the procedure in Panel A is that option prices correctly reflect the total daily volatility but not how it is split between day and night. Option prices are set assuming that instantaneous (per hour) volatilities for day and night sub-periods are the same, while they are not, as volatility is higher intraday. As a result, implied volatility in the upper-right subplot remains constant, irrespective of how many day and night periods remain. Upper-left subplot: the instantaneous volatility for the underlying alternates between being high intraday and low overnight. Both volatilities are scaled to per-unit-of-time and then annualized. The bottom-left and right subplots report average overnight and intraday excess returns for ATM straddles, respectively. Intraday returns are positive and increasing as a straddle approaches expiration (from 0.8% to almost 4%). Intraday and overnight excess returns sum to zero for a given maturity because option prices correctly reflect total daily volatility.

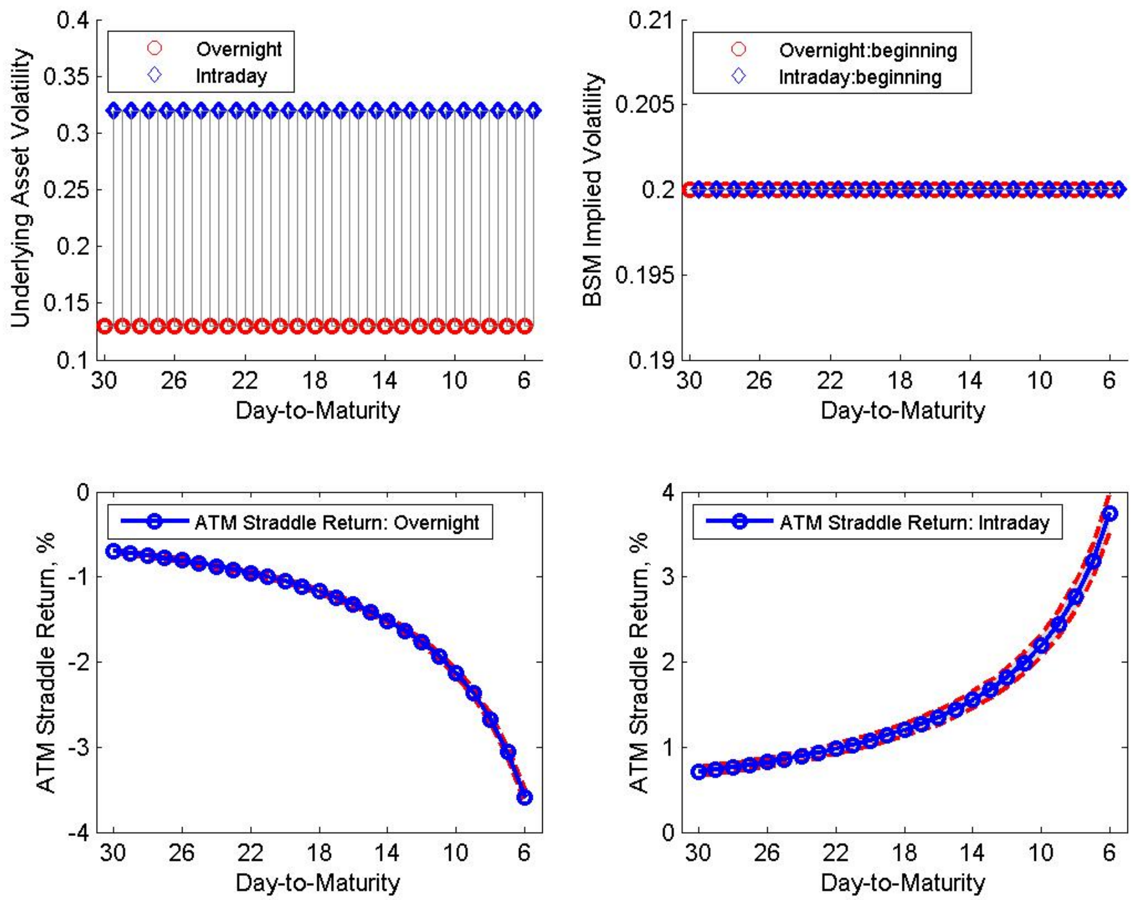

Figure 5 Day and night option returns in the Heston model

Similar to Figure 4, we study how day and night option returns depend on day-night volatility bias in the Heston model. We simulate the model separately for different levels of the day-night volatility ratio ($\sigma_{day}/\sigma_{night} = 1.6, 2.5, 3.3$), which cover a range of plausible values in the data, and then compute average option returns. Note that the volatilities in $\sigma_{day}/\sigma_{night}$ are scaled on a per-hour basis for comparability. 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 particular, *Full Bias* case $\lambda^{IV} = 1$ means the option prices completely ignore volatility seasonality and $\sigma_{day}^{IV} = \sigma_{night}^{IV} = \sigma^{IV}$. "No Bias" indicates cases when option prices are set using the correct volatility ratio $\lambda^{IV} = \lambda$.

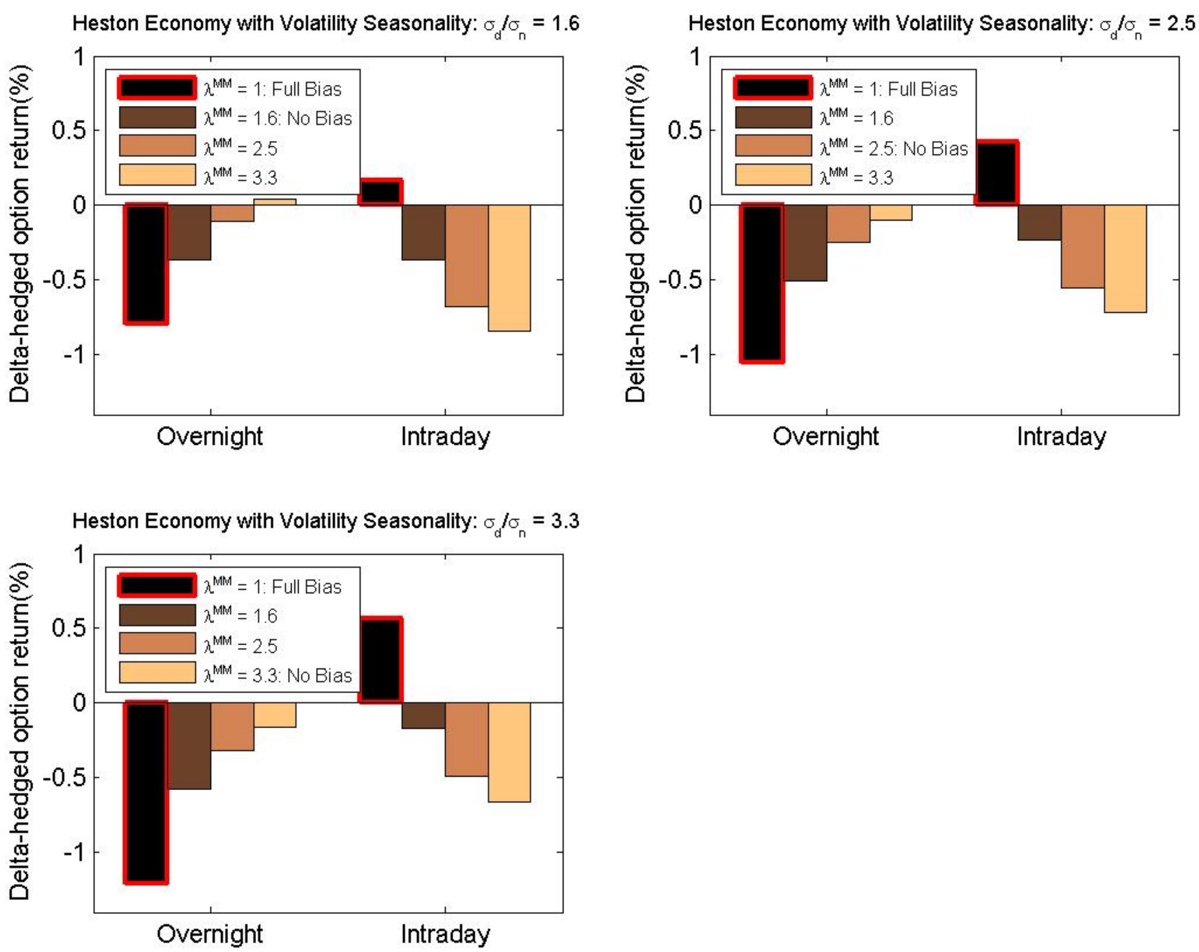

Table 1 Panel A   Day and night delta-hedged returns for S&P 500 index options

We report summary statistics for average day- and night-option returns, including mean, standard deviation, 1%, 50%, and 99% percentiles. For each day, we compute average return for all options in a given category (e.g., OTM calls) and then report the average across days. Returns are in percentage points per day (e.g., a 0.28% daily return for index options intraday). "All Deltas" include options with an absolute delta between 0.1 and 0.9. Options are delta-hedged at the beginning of each sub-period.

		Intraday Returns, %					Overnight Returns, %				
	Moneyness	Mean	Stand. Dev.	1%	50%	99%	Mean	Stand. Dev.	1%	50%	99%
All	All Deltas	0.28	4.8	-8.70	-0.38	16.19	-1.04	4.5	-9.70	-1.24	11.25
	0.1 < |Δ| < 0.25	0.27	8.0	-14.63	-0.78	28.81	-1.74	6.2	-14.65	-2.03	18.20
	0.25 < |Δ| < 0.5	0.31	4.3	-7.94	-0.26	14.05	-0.89	3.3	-8.05	-1.15	10.61
	0.5 < |Δ| < 0.75	0.15	2.0	-3.84	-0.07	6.76	-0.53	1.8	-4.13	-0.69	5.35
	0.75 < |Δ| < 0.9	0.07	0.9	-1.68	-0.03	3.20	-0.22	1.0	-2.38	-0.32	2.88
Puts	All Deltas	0.24	4.6	-8.19	-0.35	15.97	-0.90	4.1	-8.83	-1.09	12.22
	0.1 < |Δ| < 0.25	0.20	6.9	-12.01	-0.70	24.72	-1.34	5.7	-11.28	-1.72	16.12
	0.25 < |Δ| < 0.5	0.23	3.7	-6.80	-0.25	11.98	-0.83	3.1	-7.91	-0.88	8.89
	0.5 < |Δ| < 0.75	0.18	2.2	-4.33	-0.07	7.28	-0.61	2.4	-7.05	-0.63	6.73
	0.75 < |Δ| < 0.9	0.14	1.3	-2.69	-0.01	4.20	-0.22	1.8	-4.88	-0.21	5.67
Calls	All Deltas	0.28	5.3	-9.97	-0.29	17.52	-1.17	5.0	-11.05	-1.43	12.02
	0.1 < |Δ| < 0.25	0.46	10.9	-20.75	-0.72	36.30	-2.23	8.5	-20.92	-2.85	25.56
	0.25 < |Δ| < 0.5	0.39	5.1	-8.85	-0.23	17.47	-1.05	4.1	-9.73	-1.47	12.27
	0.5 < |Δ| < 0.75	0.14	2.0	-3.73	-0.05	6.52	-0.50	2.1	-4.78	-0.71	6.14
	0.75 < |Δ| < 0.9	0.08	1.0	-1.91	-0.02	3.29	-0.21	1.3	-3.39	-0.35	4.02

Table 1 Panel B Day and night equity option returns

	Moneyness	Intraday Returns, % Mean	Stand. Dev.	1%	50%	99%	Overnight Returns, % Mean	Stand. Dev.	1%	50%	99%
All	All Deltas	0.10	1.3	-2.69	-0.05	4.66	-0.41	1.1	-2.89	-0.43	3.41
	0.1 < |Δ| < 0.25	0.05	2.5	-4.97	-0.18	8.84	-0.58	1.8	-4.96	-0.65	5.52
	0.25 < |Δ| < 0.5	0.17	1.8	-3.65	-0.02	6.45	-0.49	1.3	-3.58	-0.52	4.27
	0.5 < |Δ| < 0.75	0.16	1.0	-1.91	0.04	3.84	-0.31	0.8	-2.11	-0.33	2.80
	0.75 < |Δ| < 0.9	0.16	0.6	-0.84	0.07	2.04	-0.10	0.4	-0.92	-0.13	1.50
Puts	All Deltas	0.21	1.3	-2.40	0.09	4.81	-0.49	1.2	-3.14	-0.50	3.54
	0.1 < |Δ| < 0.25	0.23	2.3	-4.04	0.02	9.05	-0.54	1.7	-4.24	-0.59	4.72
	0.25 < |Δ| < 0.5	0.29	1.5	-2.79	0.12	6.19	-0.50	1.2	-3.34	-0.51	4.02
	0.5 < |Δ| < 0.75	0.27	1.0	-1.76	0.17	3.54	-0.33	0.9	-2.31	-0.39	3.25
	0.75 < |Δ| < 0.9	0.26	0.6	-0.92	0.19	2.20	-0.12	0.6	-1.38	-0.16	1.93
Calls	All Deltas	0.07	1.8	-4.11	-0.08	6.37	-0.40	1.3	-3.80	-0.38	3.92
	0.1 < |Δ| < 0.25	0.28	4.5	-9.89	-0.11	15.60	-0.53	2.8	-7.41	-0.69	9.35
	0.25 < |Δ| < 0.5	0.25	2.6	-5.39	0.02	8.93	-0.47	1.6	-4.68	-0.48	5.42
	0.5 < |Δ| < 0.75	0.09	1.3	-2.70	-0.03	4.64	-0.29	0.9	-2.48	-0.29	2.86
	0.75 < |Δ| < 0.9	0.07	0.7	-1.34	0.02	2.42	-0.11	0.5	-1.13	-0.13	1.41

Table 2 Panel A S&P index option returns during intraday sub-periods

Each trading day is divided into five equal sub-periods. Options are delta-hedged at the start of each sub-period. “Total” column for intraday returns reports the cumulative return over all intraday sub-periods. Returns are in percentage points per day (e.g., a 0.28% daily return for index options intraday). “Excl. Weekend” column reports overnight returns excluding weekends (Friday close to Monday open). Right panel reports t-statistics that are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

		Return Average, %								**T-statistics**							
		Intraday Sub-period						**Overnight**		**Intraday Sub-period**						**Overnight**	
		1st	2nd	3rd	4th	5th	**Total**	**Total**	Excl. Week-end	1st	2nd	3rd	4th	5th	**Total**	**Total**	Excl. Week-end
All	All Deltas	-0.04	-0.02	-0.02	0.16	0.19	0.28	-1.04	-0.80	-0.8	-0.4	-0.6	4.3	3.7	2.6	-12.0	-9.4
	0.1 < |Δ| < 0.25	-0.17	-0.06	-0.05	0.26	0.27	0.27	-1.74	-1.40	-2.0	-0.9	-1.0	4.2	3.3	1.6	-14.1	-11.5
	0.25 < |Δ| < 0.5	-0.01	-0.02	0.00	0.15	0.21	0.31	-0.89	-0.73	-0.3	-0.5	0.2	4.4	3.8	3.2	-12.9	-10.2
	0.5 < |Δ| < 0.75	0.00	-0.01	0.00	0.08	0.09	0.15	-0.53	-0.44	0.1	-0.7	-0.2	4.9	4.6	3.4	-13.9	-11.8
	0.75 < |Δ| < 0.9	-0.01	0.01	-0.01	0.02	0.05	0.07	-0.22	-0.20	-0.8	1.3	-0.8	3.2	4.9	3.4	-11.2	-9.9
Puts	All Deltas	-0.06	-0.03	0.00	0.13	0.21	0.24	-0.90	-0.72	-1.3	-0.8	0.2	4.0	3.6	2.3	-10.5	-9.1
	0.1 < |Δ| < 0.25	-0.21	-0.06	0.00	0.21	0.25	0.20	-1.34	-1.11	-3.0	-1.1	0.0	3.9	3.4	1.3	-11.3	-10.8
	0.25 < |Δ| < 0.5	-0.01	-0.02	0.01	0.11	0.17	0.23	-0.83	-0.67	-0.2	-0.7	0.4	3.7	3.6	2.9	-13.0	-11.3
	0.5 < |Δ| < 0.75	0.02	-0.01	-0.01	0.09	0.11	0.18	-0.61	-0.48	0.9	-0.5	-0.8	4.6	4.7	3.8	-13.3	-10.5
	0.75 < |Δ| < 0.9	0.02	0.02	-0.02	0.04	0.07	0.14	-0.22	-0.16	1.2	1.8	-1.6	3.3	4.8	5.0	-6.5	-4.4
Calls	All Deltas	-0.03	-0.01	-0.04	0.16	0.21	0.28	-1.17	-0.95	-0.5	-0.3	-1.1	4.0	3.5	2.4	-12.6	-9.9
	0.1 < |Δ| < 0.25	-0.08	-0.04	-0.10	0.38	0.31	0.46	-2.23	-1.85	-0.7	-0.5	-1.4	4.2	2.7	2.0	-13.4	-10.5
	0.25 < |Δ| < 0.5	-0.01	0.00	0.00	0.19	0.22	0.39	-1.05	-0.89	-0.1	-0.1	0.0	4.6	3.9	3.5	-12.7	-10.0
	0.5 < |Δ| < 0.75	0.00	0.00	0.01	0.08	0.09	0.14	-0.50	-0.44	0.0	-0.2	0.5	4.7	4.3	3.3	-12.4	-10.4
	0.75 < |Δ| < 0.9	-0.01	0.01	0.01	0.03	0.04	0.08	-0.21	-0.19	-0.7	1.1	1.0	2.9	3.3	3.4	-8.2	-6.8

Table 2 Panel B Equity option returns during intraday sub-periods

		Return Average, %								T-statistics							
		Intraday Sub-period						Overnight		Intraday Sub-period						Overnight	
		1st	2nd	3rd	4th	5th	**Total**	**Total**	Excl. Week -end	1st	2nd	3rd	4th	5th	**Total**	**Total**	Excl. Week -end
All	All Deltas	0.10	-0.02	-0.04	0.00	0.05	0.10	-0.41	-0.29	7.7	-2.0	-5.7	0.1	5.7	3.0	-19.5	-13.5
	0.1 < |Δ| < 0.25	0.08	-0.05	-0.05	0.00	0.05	0.05	-0.58	-0.44	3.7	-2.7	-4.0	0.0	3.3	0.9	-16.0	-11.9
	0.25 < |Δ| < 0.5	0.14	-0.02	-0.05	0.01	0.08	0.17	-0.49	-0.35	8.5	-1.8	-5.1	1.0	6.5	4.0	-18.8	-13.2
	0.5 < |Δ| < 0.75	0.12	0.01	-0.02	0.01	0.05	0.16	-0.31	-0.21	10.8	0.8	-3.5	1.1	6.0	6.5	-19.6	-13.4
	0.75 < |Δ| < 0.9	0.09	0.03	0.00	0.01	0.03	0.16	-0.10	-0.06	14.6	5.5	0.3	2.5	4.7	11.9	-12.1	-6.9
Puts	All Deltas	0.14	0.00	-0.01	0.03	0.05	0.21	-0.49	-0.37	10.0	0.0	-0.7	2.2	4.3	6.9	-20.0	-14.6
	0.1 < |Δ| < 0.25	0.12	0.00	-0.01	0.04	0.07	0.23	-0.54	-0.41	5.5	0.0	-0.3	2.1	3.7	4.2	-15.4	-11.5
	0.25 < |Δ| < 0.5	0.17	0.01	0.00	0.04	0.07	0.29	-0.50	-0.37	10.8	0.8	-0.4	3.0	5.3	7.7	-19.1	-14.0
	0.5 < |Δ| < 0.75	0.17	0.03	0.00	0.03	0.04	0.27	-0.33	-0.25	15.4	2.9	0.5	3.9	5.1	11.7	-17.5	-12.8
	0.75 < |Δ| < 0.9	0.14	0.04	0.02	0.03	0.03	0.26	-0.12	-0.09	20.5	7.5	4.0	4.8	4.4	19.5	-10.2	-7.1
Calls	All Deltas	0.10	-0.02	-0.06	-0.01	0.06	0.07	-0.40	-0.27	4.6	-1.2	-3.5	-0.5	3.0	1.6	-16.4	-10.7
	0.1 < |Δ| < 0.25	0.22	-0.01	-0.07	0.01	0.10	0.28	-0.53	-0.35	4.9	-0.2	-2.3	0.4	2.6	2.8	-9.6	-6.1
	0.25 < |Δ| < 0.5	0.18	-0.01	-0.05	0.02	0.11	0.25	-0.47	-0.31	6.6	-0.3	-2.8	0.8	4.5	4.2	-14.6	-9.4
	0.5 < |Δ| < 0.75	0.10	0.00	-0.04	0.00	0.04	0.09	-0.29	-0.20	6.2	-0.3	-3.3	-0.3	3.2	3.1	-17.6	-11.6
	0.75 < |Δ| < 0.9	0.07	0.01	-0.01	0.00	0.01	0.07	-0.11	-0.07	7.2	1.4	-2.1	-0.2	1.6	4.8	-12.5	-7.3

Table 3 Day and night S&P 500 index option returns by year

Returns are in percentage points per day (e.g., "0.11" means an 0.11% daily return). Intraday period is divided into five equal sub-periods. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation. The last two columns compute average intraday return over the entire sample period but excludes a given year.

Year	Average Returns, %								T-statistics			Intraday Ret. Relative to Average All Years	
	Intraday Sub-period						Night	Diff.	Day	Night	Diff.		
	1st	2nd	3rd	4th	5th	Total	Total	Day - Night	Total	Total	Day - Night	Ret – Av. Ret	T-Statistics
2004	-0.29	-0.06	-0.07	0.08	0.21	-0.13	-1.1	0.97	-0.6	-13.8	4.4	-0.35	-1.6
2005	-0.16	-0.08	-0.06	0.15	0.22	0.08	-1.13	1.20	0.4	-13.1	5.6	-0.12	-0.6
2006	-0.03	-0.03	0.1	0.04	0.11	0.2	-0.98	1.15	0.9	-12.3	4.7	0.01	0.0
2007	-0.22	-0.16	0.18	0.33	0.32	0.48	-0.78	1.38	1.7	-4.6	4	0.37	1.1
2008	-0.1	0.27	0.17	0.4	0.92	1.59	-0.77	1.51	2.1	-2	2.8	0.60	1.8
2009	0.05	0.02	-0.1	-0.15	0.07	-0.11	-1.13	0.99	-0.4	-7	3.2	-0.31	-1.3
2010	0.00	-0.11	-0.12	0.13	0.06	-0.05	-1.07	0.92	-0.2	-4.8	2.4	-0.28	-1.0
2011	0.03	0.15	-0.06	0.24	0.15	0.51	-1.07	1.52	1.5	-3.7	3.3	0.34	1.1
2012	0.16	-0.11	-0.2	0.16	-0.23	-0.21	-1.12	0.89	-0.8	-4.8	2.6	-0.43	-1.6
2013	0.57	-0.11	-0.03	0.16	-0.05	0.6	-1.66	2.23	1.0	-4.4	2.5	0.43	0.7

Table 4 S&P 500 index option returns double-sorted by moneyness and time-to-expiration

Moneyness is measured as an absolute option delta. Maturity is measured as the number of trading days before option expiration. 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.

Double-sorted by 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:										
All Deltas	0.73	0.29	0.16	0.16	0.21	3.1	2.4	1.8	2.6	3.1
0.1 < |Δ| < 0.25	0.75	0.38	0.14	0.16	0.18	1.7	1.9	1.0	1.7	2.1
0.25 < |Δ| < 0.5	0.91	0.27	0.12	0.17	0.16	3.5	2.6	1.8	3.4	3.4
0.5 < |Δ| < 0.75	0.36	0.17	0.09	0.10	0.10	3.3	3.3	2.4	3.2	2.4
0.75 < |Δ| < 0.9	0.16	0.06	0.03	0.06	0.04	3.6	2.6	1.4	2.5	0.8
Overnight:										
All Deltas	-2.62	-1.00	-0.47	-0.29	-0.22	-15.6	-12.1	-8.7	-8.4	-6.5
0.1 < |Δ| < 0.25	-5.36	-1.68	-0.72	-0.44	-0.28	-16.3	-13.5	-9.3	-8.5	-5.5
0.25 < |Δ| < 0.5	-2.81	-0.90	-0.43	-0.30	-0.22	-15.2	-12.7	-10.7	-10.4	-8.1
0.5 < |Δ| < 0.75	-1.32	-0.48	-0.25	-0.16	-0.12	-15.3	-13.6	-9.7	-4.9	-3.7
0.75 < |Δ| < 0.9	-0.37	-0.17	-0.07	0.03	-0.07	-9.0	-8.9	-3.0	0.4	-1.3

Table 5 Intraday patterns in option order imbalance

Order imbalance is computed as the difference between the number of buyer- and seller-initiated trades divided by the total number of trades. We report an average over all trading days for a given category (such as index puts). A trading day is divided into five equal sub-periods. For equity options, imbalance is equally-weighted across stocks on a given day. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation. Order imbalances are in percentage points (e.g., investors, on average, purchase index puts with a daily imbalance of 3.2%). That is, out of 100 trades, about 51.6 are initiated by buyers and 48.4 by sellers. Thus, order imbalances are fairly balanced for all categories.

	Average Order Imbalance, %						**T-statistics**					
	1st	2nd	3rd	4th	5th	**Total**	1st	2nd	3rd	4th	5th	**Total**
S&P Options												
Puts	1.8	2.3	2.9	3.5	4.9	3.2	6.0	7.2	8.6	11.3	17.4	16.1
Calls	0.1	0.1	0.6	1.2	1.9	0.9	0.4	0.3	1.7	3.6	6.7	4.5
Equity Options												
Puts	-1.2	-1.9	-1.7	-1.1	-0.6	-1.7	-9.8	-14.3	-13.0	-7.8	-4.8	-14.1
Calls	-3.9	-5.3	-4.8	-4.7	-3.6	-5.5	-30.3	-37.5	-36.4	-33.8	-28.6	-41.4

Table 6 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 the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation. Only a few return predictors are marginally statistically significant.

	$OptReturn_{t+1}$, %		
	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 7 Explaining day-night option returns with day-night volatility ratio

In this table, we explore how day- and night-option returns depend on the day-night volatility ratio across stocks. The first two columns report separate Fama-MacBeth regressions for day and night option returns on just the intercept. The intercept coefficients match the day-night return asymmetry documented in Table 1 Panel B (0.1% and -0.4%). Trying to explain these intercepts/returns, the next two columns add the day-night volatility ratio to the regression. To compute 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 intercept coefficients become both negative and of similar magnitude. 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., 0.1 is 0.1% per day). T-statistics in brackets are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation. We also confirm that the absolute value of the volatility ratio $\sigma_{day}/\sigma_{night}$ coefficients in the day and night regressions are not statistically different from each other (i.e., $0.11 \cong |-0.09|$).

	$Option\ Return_{t+1}$, %					
	Day	Night	Day	Night	Day	Night
$Intercept$	0.1	-0.4	-0.17	-0.25	-0.03	-0.07
	(3.6)	(-18.6)	(-2.7)	(-7.2)	(-0.4)	(-1.3)
$\sigma_{day}/\sigma_{night}$			0.11	-0.09	0.11	-0.08
			(15.1)	(-11.6)	(11.5)	(-7.4)
$AbsStkRet_t$					-25.2	-8.0
					(-3.0)	(-0.7)
$OptBASpread_t$					-0.5	-0.1
					(-0.9)	(-0.4)
$ImpliedVol_t$					1.4	-0.02
					(3.0)	(0.0)
$IVSkew_t$					-0.1	1.1
					(-0.2)	(3.3)
$OptVolume_t$					0.0	0.0
					(-2.2)	(2.6)
$VarRiskPrem_t$					-36.0	-14.6
					(-4.0)	(-1.3)
$IVSpread_t$					-0.6	-1.5
					(-3.2)	(-3.4)
$Adj. R^2$ (%)	0.0	0.0	0.4	0.2	2.9	2.2

Table 8 Option returns for portfolios sorted on day-night volatility ratio

In this table, we use portfolio sorts to explore how day and night option returns depend on the day-night volatility ratio. We sort stocks into five portfolios based on the historical day-night volatility ratio. For each portfolio, we report average volatility ratio, intraday and overnight option returns, as well as the return difference with the corresponding t-statistics. To compute 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. Returns are in percentage points per day (e.g., -0.33 is -0.33% per day). T-statistics are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

	$\frac{\sigma_{day}}{\sigma_{night}}$	Option Return, %			
		Overnight	Intraday	Diff.	T-Stat.
Low, 1	1.6	-0.33	-0.03	-0.3	-5.8
2	2.5	-0.43	0.09	-0.51	-8.7
3	3.0	-0.44	0.14	-0.58	-9.8
4	3.6	-0.47	0.19	-0.67	-11.3
High, 5	4.9	-0.52	0.26	-0.78	-13.9
High - Low		-0.19	0.29		
T-Stat		-11.2	18.4		

Table 9 Intraday volatility seasonality as a test for alternative explanations

Panel A. Intraday seasonality in equity option returns. The table reports Fama-MacBeth regressions for equity option returns for three intraday sub-periods (morning, noon, and afternoon) on just the intercept. Thus, the intercept coefficients simply corresponds to average option return for a given sub-period (i.e., 0.139% return per day). The last two columns show that the difference between intraday returns is statistically significant. The returns differ slightly from Table 2, as we require all the control variables in Panel C to be well defined to make it comparable with Panel A. T-statistics in brackets are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

	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 sub-periods 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 7, option returns in a particular intraday sub-period (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 sub-period stock returns over the preceding 60 days. Compared with Panel A, the intercept coefficients that correspond to abnormal option returns become both statistically and economically insignificant. The fourth and last columns add several controls, including absolute stock return, option bid-ask spread, option volume, option implied volatility, volatility skew, and variance risk-premium.

	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 10 A test based on leverage-adjusted returns for S&P500 index options

Conventional option returns display more extreme day-night return asymmetry for short-term options in Table 4, perhaps because they have the highest leverage. However, the volatility bias implies that even after adjusting for leverage, short-term options should have more pronounced day-night asymmetry. We first confirm this hypothesis in simulated returns from the BSM model with volatility seasonality and volatility bias. The simulation results are reported in the top panel. Standard errors for simulated returns are small, so we do not report them. The bottom panel reports leverage-adjusted returns observed in the data. The last column compares short-term option returns (between 4 and 15 trading days to maturity) and mid-term options (between 16 and 53 days) to confirm indeed even after adjusting for leverage, short-term options have more pronounced day-night return asymmetry. Option delta hedged returns are adjusted for implied leverage as described at the end of Section 3. Maturity is measured in trading days before expiration. Returns are in percentage points per day (e.g.,"-0.105" is -0.105% per day). The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

Simulations:	Average Return for Given Maturity		
	4-15 days	16-53 days	Difference
Intraday:	0.013	0.007	0.006
Overnight:	-0.105	-0.057	-0.048
Data:			
Intraday:	0.021	0.012	0.009
	(2.93)	(1.81)	(2.04)
Overnight:	-0.061	-0.038	-0.023
	(-11.25)	(-9.81)	(-4.94)

Table 11 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 7. After controlling for day-night volatility seasonality, (i) the intercept becomes negative in both day and night regressions, and (ii) the coefficients for the volatility ratio have the same absolute value but differ in sign $\beta_{day}^{\lambda} = -\beta_{night}^{\lambda}$. 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. As in Table 7, the volatility ratio is computed in two steps. We first compute intraday (overnight) volatility from open-to-close (close-to-open) stock returns from the preceding 60 days, annualize them, and then compute their ratio. 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 7.

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

Table 12 Price pressure and option returns

Panel A. Baseline specification. Panel A reports Fama-MacBeth regressions of day and night option returns on the day-night volatility ratio. The procedure is identical to the cross-sectional test in Table 7 except that we use the subsample with available order imbalance data to make it comparable to Panel B. After controlling for the day-night volatility ratio, the intercept for intraday returns switches sign from positive to negative and becomes comparable to the overnight intercept. Returns are in percentage points per day (e.g., 0.16 is 0.16% per day).

	$OptReturn_{t+1}$, %			
	Day	Day	Night	Night
$Intercept$	0.16	-0.17	-0.51	-0.25
	(2.5)	(-2.7)	(-20.6)	(-7.2)
$\sigma_{day}/\sigma_{night}$		0.11		-0.09
		(15.1)		(-11.6)
$Avg. R^2$, %	0	0.36	0	0.19

Panel B. Adding demand pressure to the baseline specification. Panel B adds price pressure measures to Fama-MacBeth regressions in Panel A. We compute order imbalance as the difference between the number of buys and sells normalized by the 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 from the ISE, the imbalances are computed using the cumulative number of buys and sells by non-market makers. Order imbalances are for the previous day (t), the day before that (t-1), and the average over the previous month (1M). The controls include 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.

	$OptReturn_{t+1}$, %							
	Day	Day	Day	Day	Night	Night	Night	Night
$Intercept$	-0.15	-0.13	-0.10	0.03	-0.24	-0.23	-0.08	0.00
	(-2.4)	(-1.8)	(-0.9)	(0.3)	(-6.5)	(-5.7)	(-1.1)	(-0.0)
$\sigma_{day}/\sigma_{night}$	0.11	0.10	0.14	0.11	-0.09	-0.10	-0.07	-0.07
	(13.6)	(12.0)	(5.4)	(12.2)	(-11.2)	(-11.4)	(-6.1)	(-4.9)
$OImb\_Intraday_t$	0.34		0.33		0.22		0.19	
	(18.0)		(10.5)		(6.9)		(5.9)	
$OImb\_Intraday_{t-1}$	0.14		0.04		0.04		0.06	
	(10.0)		(0.4)		(1.0)		(1.3)	
$OImb\_Intraday_{1M}$	0.19		0.24		-0.08		-0.06	
	(5.5)		(4.9)		(-0.1)		(-0.8)	
$OImb\_OpenClose_t$		0.28		0.26		0.00		0.01
		(17.8)		(16.8)		(-0.1)		(0.4)
$OImb\_OpenClose_{t-1}$		0.12		0.12		0.00		0.01
		(11.5)		(11.5)		(0.1)		(0.2)
$OImb\_OpenClose_{1M}$		0.28		0.25		-0.06		-0.07
		(8.0)		(7.1)		(-0.8)		(-0.9)
$Controls$	-	-	+	+	-	-	+	+
$Avg. R^2$, %	0.84	0.81	3.39	3.8	0.55	0.59	2.37	2.67

Table 13 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. Overall, according to the maturity bias, intraday-option returns are close to zero, while night returns are negative, which roughly matches the observed option 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 variance risk premium. It then reports average intraday option returns by maturity and moneyness for two levels of stock volatility, $\sigma = 15\%$ and $\sigma = 30\%$. These simulations confirm that according to the maturity bias, day-night option returns do not depend 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%

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 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.10 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 5. 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 5 by a 3% typical effective bid-ask half-spread produces a 0.09% expected bias, which matches the price difference in Table A.10. 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 sub-period cut-off is small, and the benefits of frequent delta-hedging are small.

Panel B of Table A.10 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.2 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.9 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.9, 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.3 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 10% percentiles 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.4 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,

$$\frac{dS_t}{S_t} = \mu dt + \sigma_t dB_t, \tag{A.1}$$

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:

$$\begin{aligned} Call_t &= S_t N(d_1) - K e^{-r_f(T-t)} N(d_2), \\ Put_t &= K e^{-r_f(T-t)} N(-d_2) - S_t N(-d_1), \end{aligned} \tag{A.2}$$

where

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

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

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. For example, for overnight returns, we first compute the option price at the close with Equation (A.2). We then simulate close-to-open returns for the underlying using Equation (A.1), and compute open price for the same option using Equation (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 Equations (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? Equation (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.5 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,

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

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 $\rho < 0$ in order to reflect the leverage effect.

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

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

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

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,

$$SV_t = \begin{cases} V_t^{day} = \nu^{day} V_t \\ V_t^{night} = \nu^{night} V_t \end{cases},$$

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

$$V_t = \frac{17.25}{24} V_t^{night} + \frac{6.75}{24} V_t^{day} \tag{A.5}$$

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

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 Equation (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 Equations (1) and (2).

A.6 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.[22] For example, 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.

[22] We focus on the bid-ask spread as it is typically much larger than other option costs, such as hedging costs in the underlying (e.g., Figlewski, 1989), 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 (2015), 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.18, we compare overnight returns and trading costs for SPY options. Results are reported for two sub-periods: 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 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. 95% confidence intervals are also reported.

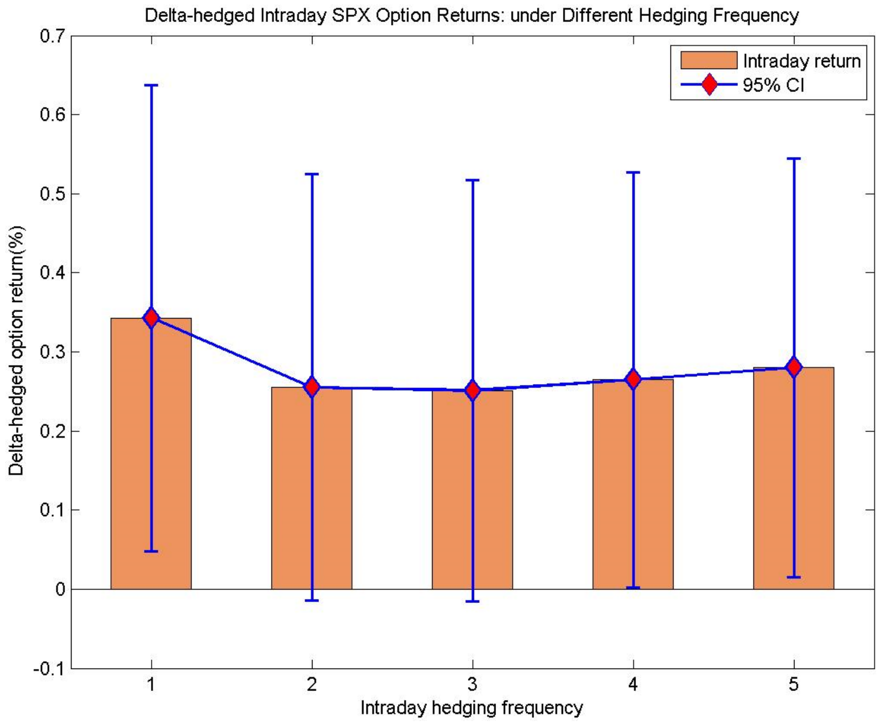

Figure A.2 Day (open-to-close) and night (close-to-open) volatility for individual stocks

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-day basis (24h) to make them comparable before computing their simple ratio.

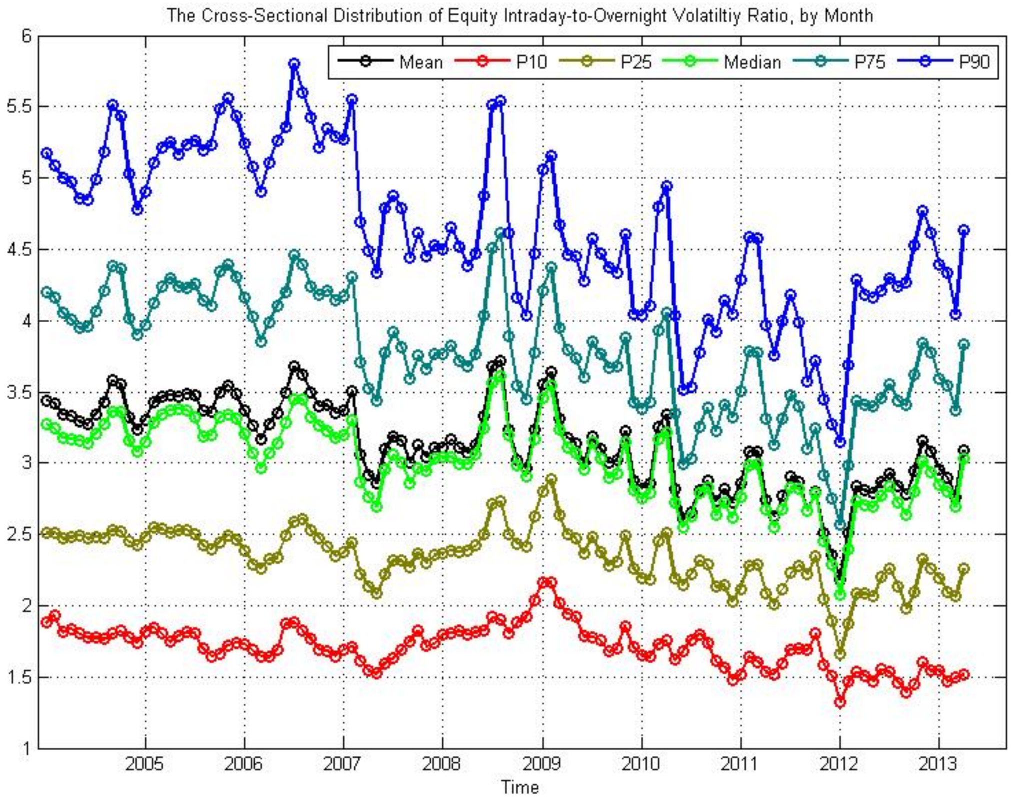

Figure A.3 Day and night option returns in the Black-Scholes-Merton model

We study how day and night option returns depend on the day-night volatility bias in the BSM model. Model parameters are set to match the historical data (i.e., implied volatility is set higher than realized). We simulate the model separately for different levels of the day-night volatility ratio ($\sigma_{day}/\sigma_{night} = 1.6, 2.5, 3.3, 4.1$), which covers a range of plausible values in the data and then compute average option returns. Note that the volatilities in $\sigma_{day}/\sigma_{night}$ are scaled on a per-hour basis to make them comparable. Each graph shows how night and day returns depend on the degree to which option prices underreact to the day-night volatility seasonality. While the actual seasonality is $\lambda = \sigma_{day}/\sigma_{night}$, option prices are set assuming a different ratio $\lambda^{IV} = \sigma_{day}^{IV}/\sigma_{night}^{IV}$ (i.e., option investors have biased beliefs). In particular, a *Full Bias* case means that option prices completely ignore volatility seasonality and treats: $\sigma_{day}^{IV} = \sigma_{night}^{IV} = \sigma^{IV}$. "No Bias" indicates cases where option prices are set using the correct volatility ratio $\lambda^{IV} = \lambda$.

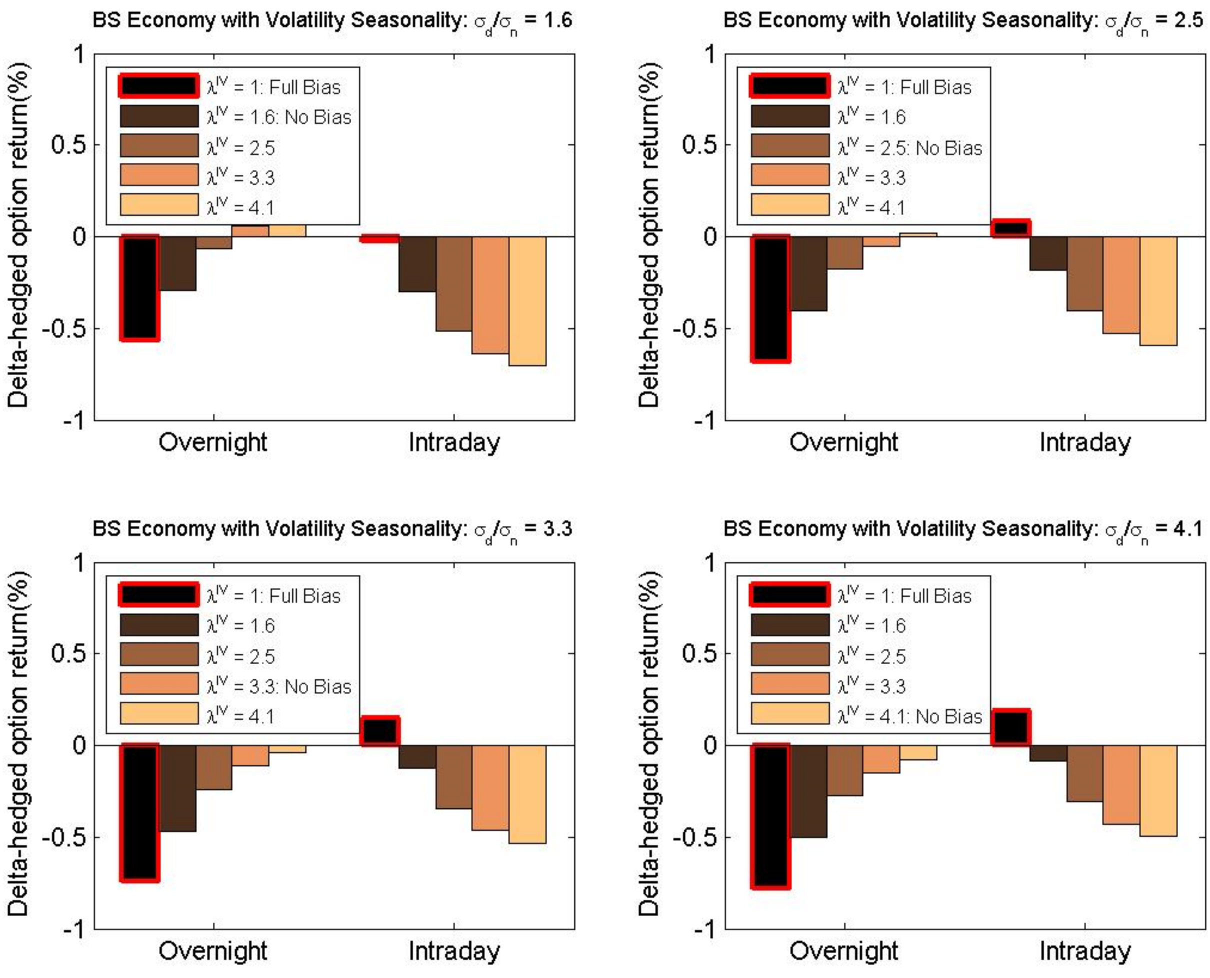

Table A.1 Summary statistics for day and night returns for S&P500 index and individual stocks

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 Day and night option returns for major ETFs

This table reports average stock volatility and option returns for overnight and intraday periods for selected ETFs. These ETFs have the most actively traded options in a given sector. Returns and volatilities are in percentage points per day. Stock volatility is measured as a standard deviation of intraday or night stock returns and are not annualized. The t-statistics in the last two columns are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation. Overall, this table provides important examples of how day-night returns asymmetry and day-night volatility vary across ETFs.

		Stk. Volatility, %		Opt. Ret., %		T-Stat. Opt. Ret.	
Ticker	Description	Intraday	Overnight	Intraday	Overnight	Intraday	Overnight
SPY	S&P 500	1.0	0.7	0.17	-0.49	3.1	-12.5
QQQ	NASDAQ 100	1.1	0.7	0.14	-0.39	3.0	-14.2
IWM	Russell 2000	1.4	0.8	0.15	-0.58	3.1	-18.2
DIA	Dow Jones	0.9	0.6	0.15	-0.61	2.4	-13.5
	International ETFs						
EEM	MSCI Emerg. Markets	1.5	1.5	-0.17	-0.20	-2.3	-4.2
EFA	MSCI EAFE (Europe)	1.1	1.2	-0.08	-0.05	-0.8	-0.7
FXI	China Large-Cap	1.4	1.8	-0.14	0.04	-1.9	0.6
EWZ	MSCI Brazil	1.9	1.7	-0.02	-0.17	-0.2	-2.9
	Industry ETFs						
IBB	Nasdaq Biotech.	1.2	0.8	0.23	-0.62	3.0	-7.6
XHB	S&P Homebuilders	2.2	1.4	0.09	-0.35	1.2	-8.3
XLE	Energy Sector	1.5	1.1	0.12	-0.30	2.0	-7.1
XOP	Oil&Gas Expl&Prod.	2.0	1.5	0.08	-0.32	0.6	-2.9
XLF	Financial Sector	1.8	1.2	0.06	-0.34	0.8	-8.2
XLV	Health Care Sector	0.8	0.7	0.00	-0.57	0.1	-6.7
IYR	DJ US Real Estate	2.0	1.0	0.10	-0.51	1.3	-9.2
	Commodities and IR						
USO	Oil	1.7	1.4	0.04	-0.43	0.5	-6.9
GLD	Gold	1.4	1.1	0.29	-0.70	2.6	-8.0
TLT	20+Y Treasury Bond	0.6	0.6	-0.14	-0.30	-2.1	-5.5

Table A.3 Option returns by year.

Panel A. Returns for equity options

Year	Average Returns, %								T-statistics		
	Intraday Sub-period						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 Sub-period						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.4 Alternative null hypothesis for option returns

This table compares average da-y and night-option returns observed in the data with two null hypotheses. First, the Black-Scholes-Merton model without the variance risk-premium implies zero excess option returns in both subperiods. The second null hypothesis is based on the Heston stochastic volatility model with parameters that match the observed data. The Heston model implies negative variance premium and thus negative returns for both day and night periods. We repeat the same analysis in the last two columns, except we exclude the financial crisis (September 2008 through January 2009) from the sample. The t-statistics are computed for a given null hypothesis using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

	Full Sample		Excluding the Crisis	
	Intraday	Overnight	Intraday	Overnight
Data, Average Return	0.28%	-1.04%	0.17%	-1.05%
H0: Black-Scholes Model with no VRP				
Average Return	0.00%	0.00%	0.00%	0.00%
T-Statistics	2.57	-11.95	1.36	-17.30
H0: Heston Model				
Average Return	-0.55%	-0.24%	-0.55%	-0.24%
T-Statistics	7.69	-9.14	5.66	-13.27

Table A.5 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 (~252 trading days in calendar year). 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 for heteroscedasticity and autocorrelation.

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.6 Option returns by time-to-expiration

Maturity is measured as the number of trading days before expiration (~252 trading days in calendar year). Each trading day is divided into five equal sub-periods. "Total" column for intraday returns reports the cumulative sum of sub-period 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 Sub-period						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.7 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 for heteroscedasticity and autocorrelation.

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.8 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. 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.9 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 sub-periods. The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

Panel A Straddle returns

	Return Average, %							T-statistics						
	Intraday Sub-periods						Overnight	Intraday Sub-periods						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 Sub-periods						Overnight	Intraday Sub-periods						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.10 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. We split every day into five equally long sub-periods. 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.). Returns are in percentage points per day (e.g., "0.44" means a 0.44% daily return). The t-statistics (right panel) are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

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

	Intraday Sub-period					
	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.11 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.12 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). Intraday period is divided into five equally long sub-periods. 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 for heteroscedasticity and autocorrelation.

Maturity, days	**Return Average, %**							**T-statistics**						
	Intraday Sub-periods						**Overnight**	**Intraday Sub-periods**						**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.13 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. Returns are in percentage points per day. The t-statistics are computed using the Newey-West (1987) adjustment for heteroscedasticity and autocorrelation.

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.13 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). Returns are in percentage points per day. 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.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 7 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 7. 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 intercept coefficients become both negative and of similar magnitude. 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 for heteroscedasticity and autocorrelation.

	$Option\ Return_{t+1}$, %					
	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 here. 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%. For the day-night volatility ratio, λ, or $\sigma_{day}/\sigma_{night}$, we use a range of plausible values that spans historical variation in this ratio.

	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.

	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

*: 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.

Table A.16 Order imbalance summary statistics and correlations
We compute order imbalance as 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. The correlation between open-close and intraday imbalances is relatively low.

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.17 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.18 Trading strategy

We compare overnight option 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 sub-periods: 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%