Market Return Around the Clock: A Puzzle[☆]

Oleg Bondarenko[a] and Dmitriy Muravyev[b]

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Abstract

We study how the excess market return depends on the time of the day using E-mini S&P 500 futures that are actively traded for almost 24 hours. Strikingly, four hours around Asian markets' close and European open account for the entire average market return. This period's Sharpe ratio is extremely high as overnight volatility is low. Its returns are positive in every year and survive transaction costs. Remarkably, average returns are zero during the remaining 20 hours and almost all sub-intervals. We attribute high returns around European open to the uncertainty resolution as European investors help process information accumulated during Asian trading hours. Consistent with this hypothesis, VIX future returns are positive during the Asian session and highly negative around European open.

JEL Classification: G12, G13, G14

Keywords: Market return, intraday data, uncertainty resolution, index futures

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[a] Department of Finance, University of Illinois at Chicago, 601 S. Morgan St., Chicago, IL 60607. Tel.: +1 (312) 996-2362. E-mail: olegb@uic.edu

[b] Department of Finance, Michigan State University, Eppley Center, 667 North Shaw Lane, East Lansing, MI 48824. Tel.: +1 (517) 353-5793. E-mail: muravyev@msu.edu

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1. Introduction

We study how excess market return as reflected by S&P 500 index changes over day and night. This exercise is possible because E-mini S&P 500 futures are actively traded at night.[1] E-mini S&P futures returns equal excess returns on S&P 500 index. The E-mini overnight session starts at 6:00 p.m. Eastern Time (ET) and spans almost 24 hours with a short break after US close. Figure 1 shows how cumulative returns of E-mini futures depend on the time of the day. Average returns during one period clearly stands out. After being zero-flat during the first part of the overnight session, the cumulative returns rapidly increase between 11:30 pm and 3:30 am and afterwards become flat again. During the 2004 to 2018 sample period, these four hours have a 7.6% annualized return. We call this period "EU-open," as it corresponds to deep night in the U.S., late afternoon in Asia, and early morning in Europe. Asian markets close and European markets open during EU-open. In contrast, returns during the rest of the day are only -0.8% p.a., or virtually zero, and are flat for the entire day except around US close.[2]

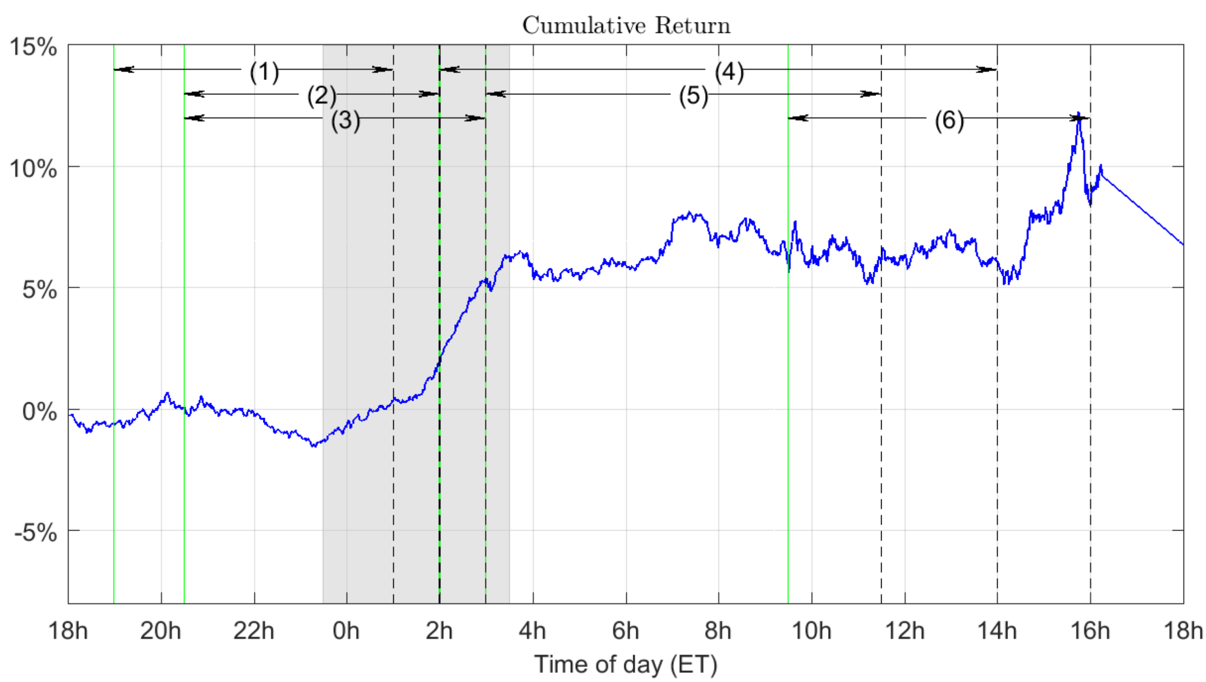

Figure 1. Annualized average cumulative log returns for S&P 500 E-mini futures as a function of time of the day. Line arrows denote open and close times for major equity markets (Japan, China, Hong Kong, Frankfurt, London, and US). The market is mostly closed from 4:15 pm to 6:00 pm. EU-open period is in grey. Time of day is in Eastern Time (ET).

[1] S&P 500 E-mini futures provide an excellent proxy for excess market return, which is standard in the market return predictability literature. By no arbitrage, it closely tracks the underlying index. Hasbrouck (2003) shows that E-mini futures lead the spot index and account for most price discovery.

[2] Our sample starts in 2004 because most E-mini volume shifted to electronic trading, and overnight volume increased ten-fold. Annualized return equals period return times 252, the number of trading days in a year.

These new stylized facts shed light on how market return and equity premium are formed at the micro level. Equity premium has been extensively studied, usually at the monthly or longer horizons. Of course, a month consists of days, and daily average returns are only positive during EU-open. Also, most theories of equity premium struggle to explain high the EU-open puzzle. They imply that expected market return should be proportional to risk. Market conditions vary drastically and systematically over a day. For example, average trading volume and volatility are particularly high during regular US trading hours. Therefore, theories have distinct predictions about which parts of a day are particularly risky and thus should carry a higher premium. According to most theories, expected returns should be positive in all intraday intervals. However, market returns are insignificant outside the four-hour overnight period with low volatility.

Returns are not only high during EU-open, but also less risky by most conventional measures. Realized volatility is 3.9 times lower during EU-open than during the rest of a day. Annualized Sharpe ratio is 1.67 compared to zero for the rest of the day. Even though four hours constitute 1/6th of a trading day, EU-open contributes only 8.3% to daily return variance during our sample period. EU-open returns are positively skewed, which makes this period arguably even less risky, as many investors prefer positive skewness. In contrast, return skewness is negative during the rest of the day. Maximum daily loss and drawdown are only 4.5% and 8%, respectively, compared to 8.5% and 66.4% for the rest of the day. Only return kurtosis is higher during EU-open which is mostly due to much lower volatility and a few large overnight returns. Overall, if anything EU-open appears less risky than the rest of the day, which deepens the return puzzle.

Following the literature, expected returns are computed as an average of realized returns from a single time series and thus can be sensitive to a given sample period. However, EU-open returns are extremely robust. A 7.6% annualized return is highly statistically significant with a *t*-statistic of 6.4. EU-open returns are significant for every calendar year, month, and weekday. In contrast, cumulative return during the rest of the day is zero (*t*-statistic of -0.2), and no other intraday interval comes close to EU-open return. Consider a one-hour moving window that shifts every minute through a day. The moving window *t*-statistic for average returns reaches six during EU-open while returns for only three other hourly intervals touch a 1% significance threshold: around 7:30 pm, 7:00 am, and 3:00 pm. EU-open is the only statistically significant period if the moving window is extended to four hours. EU-open returns are remarkably robust while returns are insignificant for almost all other intraday intervals, which is an equally puzzling fact.

It is usually assumed that futures are illiquid outside of their regular trading hours. E-mini S&P futures are an exception. During the regular US trading session, E-mini S&P is by far the most liquid index product, especially for trading in size. However, it also remains one of the most actively traded index contracts during the Asian and European trading hours.[3] In a typical EU-open period, $14 billion of S&P index exposure is traded with almost two hundred trades per minute. Although the Asian trading session is least active, trading costs remain low during EU-open. The bid-ask spread is almost always one tick, including US and Asian sessions, and is only 1.7 basis points on average. Market depth, the size available at the best bid and ask, is about $5.6 million. Thus, EU-open and Asian sessions are liquid: investors can trade in large size and take liquidity fast and at low cost.

These results suggest a simple trading strategy to earn market returns: buy futures right before EU-open and close position after the period ends. This strategy is easy to automate as E-mini futures are traded electronically, but it requires trading twice a day, which incurs significant trading costs. However, it remains profitable after costs despite frequent trading. We assume investors pay exchange fees, commissions, and the entire bid-ask spread to execute trades immediately. It is an upper bound on trading costs as costs can be reduced by providing liquidity. Limit orders are filled within seconds. The after-cost annualized average return, *t*-statistic, and Sharpe ratio are 2.6%, 2.1%, and 0.55, respectively. Thus, costs reduce the profitability by two-thirds, but returns remain significant. The baseline strategy can be substantially improved by only trading when expected EU-open returns are expected higher than average. This conditional strategy relies on a linear model that predicts EU-open returns with two ex-ante variables: VIX daily change and volatility during the Asian session. These predictors are motivated by the uncertainty resolution hypothesis: EU-open returns should be higher when uncertainty increases as measured by higher VIX or Asian volatility. This model shows an impressive out-of-sample R^2_{OS} of 6.6%. The strategy only trades when expected profits exceed 1.5 times costs, or about 40% of days. Per-day profitability more than doubles while costs remain the same. The conditional strategy has an annual cumulative return of 4.6% and Sharpe ratio of 1.2 after costs. Under these simplifying assumptions, we estimate that the capacity of these strategies is about nine billion

[3] For example, CME Group (2017) estimates that E-mini S&P 500 futures are the 4th most actively traded equity index future in Asia with an average daily turnover of $7.1T during the Asian session, which is surpassed only by Hang Seng ($15.5T ADV), KOSPI 200 ($12T), and OSE Nikkei index futures ($8.2T). Of course, E-mini's trading volume increases five-fold once the Asian session ends and European session starts.

dollar that translates into average after-cost profits of about 50 million dollars per year. Long-term investors can also benefit from the EU-open anomaly by timing their trades. If a long-term investor wants to buy an E-mini future, then the best timing is before EU-open (or after EU-open for sells). Thus, investors benefit from high EU-open returns, while they are not compensated for holding market risk during the rest of the day. Overall, the trading strategy (1) is highly profitable net of conservative estimates of trading costs, (2) has enough capacity to earn fifty millions dollars per year, and (3) can be greatly improved if one only trades on days with high uncertainty prior to EU-open, and this timing strategy has an unusually high out-of-sample R^2.

After discovering the EU-open puzzle, we conduct several tests to explain it. Asian market close and European open are the only important recurrent events during this four-hour period. We use the change in daylight saving time as a natural experiment to disentangle the impact of Asia and Europe. Since Asia does not observe daylight saving time, Asian time shifts by one-hour relative to Europe for about half a calendar year. The run up in price during EU-open stays unchanged relative to European time and thus shifts in Asian time even though Asian closing times do not shift. Thus, the EU-open price run up stays in European and not Asian time, allowing us to conclude that the Asian close does not drive the puzzle.

After establishing that high EU-open returns are triggered by European open rather than Asian close, we explore potential explanations for this effect including conventional price risks, investor sentiment, carry costs, news arrival, financial frictions such as inventory risk, and the uncertainty resolution. Some of these hypotheses, especially the uncertainty resolution, are helpful for explaining high EU-open returns. However, they struggle to explain why returns are zero during the rest of the day, even though this 20-hour period is longer and arguably riskier.

The uncertainty resolution hypothesis comes closest to explaining the puzzle. By price uncertainty we mean that market prices deviate from fundamental value, an unobserved price that reflects all public information after proper risk adjustment. Public information is not always fully processed. Price uncertainty can be quantified as a standard deviation of the difference (or distance) between price and fundamental value. High uncertainty leads to a price discount as an asset is riskier when its price is further away from fundamental value. However, investors cannot tell whether it is overvalued or undervalued. Several theories formalize this argument and help us understand how the uncertainty resolution during EU-open can produce high returns. Hu, Pan, Wang, and Zhu (2019) argue that the uncertainty resolution leads to the pre-FOMC drift and show in a stylized model that when uncertainty is resolved, prices increase but volatility can stay relatively low. Hong and Wang (2000) study average returns, volatility, and volume around market closures that "can be broadly interpreted as periods when a subset of investors withdraws from the market." In their model, prices increase endogenously as information asymmetry is resolved around market open. As market price deviates from fundamental value, uninformed investors are only willing to buy the asset at a discount. Similarly, Easley and O'Hara (2004) study how the total amount of information affects asset prices. They show that a lower fraction of informed traders makes the stock riskier for both informed and uninformed investors, thus increasing expected returns. Expected returns increase because when information is private, rather than public, uninformed investors cannot infer information from prices, and consequently they require higher return. In these theories, the more information (through public or private signals) prices reflect, the smaller the price discount is relative to fundamental value.

During the US and European sessions, many important investors are active and keep E-mini price close to fundamental value. Hence, price uncertainty is low during most of the day, except uncertainty can accumulate during the Asian sessions as fewer investors are active and have limited capacity to process public information. Some of the world's major investors are asleep. Conversely, uncertainty is resolved during the EU-open. Large European investors return to the market and push E-mini prices towards fundamental value. European investors need not exploit private information; they can simply interpret public Asian news, including any price relevant information, independently from Asian investors.[4] Price uncertainty can be due to the size gap between the Asian economy and its asset management industry. Although Asia is the world's economic powerhouse, few large investors operate in this time zone.[5]

Several results support this hypothesis. First, traders' composition changes during EU-open: the E-mini trade size is lowest during the Asian session and starts increasing through EU-open as large investors return to the market. Second, EU-open returns should be increasing in price uncertainty accumulated overnight. Trading volume and realized volatility are high when

[4] Alternatively, all investors can be equally informed. Each investor observes an independent private signal about fundamental value. During the Asian session, price reflects only Asian investors' signals while Europeans sleep. During EU-open, uncertainty is resolved as prices now reflect all signals, thus making prices more informative.

[5] According to the International Monetary Fund (2019), Asia contributes \$31.6T toward the world's GDP, more than North America's and Europe's \$24.4T and \$21.8T, respectively. Thus, Asian news is important for the world economy, but few large investors operate in this time zone and can fully interpret the news. Indeed, the 2017 survey shows that AUM in Asia is \$4,58T, or 2.75 times lower than in Europe and 6.7 times lower than in the U.S.

information is released and thus reflect increased uncertainty. We find that EU-open returns are substantially higher following high volatility or volume during the Asian session. Third, a variance ratio test (Amihud and Mendelson, 1987) shows that prices are less informationally efficient during the Asian session compared to the rest of the day. Specifically, daily returns based on pre-EU-open prices have higher variance than daily returns from post-EU-open prices, suggesting that pre-EU-open prices contain more noise. The variance ratio steadily declines during EU-open. Fourth, EU holidays are days when uncertainty is not being resolved during EU-open. Indeed, EU-open returns are slightly *negative* when EU stock markets are closed but the US market is open. On EU holidays, returns are positive during the rest of the European session when US investors finally arrive and resolve uncertainty. Fifth, price uncertainty is often measured using changes in VIX (e.g., Hu et al., 2019). Indeed, EU-open returns are higher if VIX increases on the previous day. Finally, our main test relies on VIX future returns. Strikingly, VIX returns are positive through the Asian session, indicating increased uncertainty. But the positive VIX trend stops as EU-open begins, and VIX returns start to decline before Europe opens. VIX returns during EU-open are highly negative. Uncertainty, as reflected by VIX future prices, rapidly declines during the second part of the EU-open, while cumulative market returns rapidly increase. Thus, patterns in the market return and VIX futures return are consistent with the uncertainty resolution hypothesis.

We explore other potential explanations. Conventional risk-based theories attribute higher expected returns to risk factors, as reflected by systematic volatility, price and volatility jumps, and negative skewness, among others. But all these risk measures are lower during EU-open as compared to the rest of the day. The peso problem cannot explain why EU-open returns differ so much from returns in adjacent periods. EU-open is less risky compared to other intraday intervals but commands much larger risk premium. The investor sentiment hypothesis argues that European investors are buying at the open because they are more optimistic than everyone else. However, EU-open returns do not depend on sentiment measures. Market return can be higher to compensate for carry costs such as interest rates and margin payments that are typically incurred overnight. Most carry costs increase in interest rates, but EU-open returns are uncorrelated with them. Furthermore, carry costs are incurred every calendar day and thus are higher over weekends, yet EU-open returns are slightly lower over weekends. Finally, perhaps, close-to-open stock returns are positive because most news arrives at night (McCrum, 2018). Indeed, market-moving US news such as earnings announcements, analyst forecast revisions, and many macro news are released shortly before US open or shortly after US close. But EU-open occurs while the US is in deep night, which is at least five hours away from these news intensive periods. Even European macro announcements are at or after the end of EU-open. News flow is generally low during EU-open.

We next consider inventory risk, which arises because liquidity providers are risk-averse and have limited capital. Dealers must accommodate customer order flow and thus hold suboptimal portfolios. Hence, they require a premium for holding this inventory risk, which increases in the size of an undesired position, asset volatility, dealer's risk aversion, and expected holding period (this idea goes back to at least Stoll (1978)). For example, Bessembinder (1992) shows that returns for some futures vary with the net holdings of hedgers, after controlling for systematic risk. Perhaps, some European investors avoid holding positions overnight by selling them at the US close and buying them back at European open. Their collective price pressure decreases prices around the close while also causing prices to rebound around the open. This pattern coincides with EU-open and thus potentially could explain the EU-open price run up.

Inventory risk seems intuitive and plausible; however, on a closer look, this hypothesis faces numerous challenges. Its predictions simply do not line up with the data. First, hedging overnight risk requires daily trading, and trading costs add up quickly, making such hedging prohibitively expensive. Second, if investors want to hedge overnight, waiting until EU-open is a waste of time. With an average hourly volume of 2.4 billion dollars during pre-EU-open, the Asian session can easily accommodate large trades. Throughout the day, the bid-ask spread is almost always one tick, and thus trading costs are comparable to the more liquid European session. Third, if prices rebound so strongly around EU-open, then an equally large price drop should be around European or US close, but returns are close to zero and if anything, more positive before US close. Why are investors so scared of the Asian trading session? The ten-hour period between US close and European open represents only 12% of total return variance. The time it takes to have a long lunch in the middle of the US session carries almost the same amount of risk as sleeping through the entire Asian session. Why do dealers receive compensation only during EU-open but not during the rest of the night? This is the biggest challenge for the inventory risk hypothesis as returns are slightly negative during the Asian session pre EU-open. Thus, dealers are not compensated for holding inventory during these six hours, which contradicts inventory risk models. A front-runner, who carries no inventory risk at night, can earn the same return as the dealer by buying right before EU-open. As we show, this strategy is profitable after costs. This investor can further boost profits by buying at the bid, no penalty for an unexecuted limit order. Finally, expected order imbalances must be reflected in prices in advance. If European investors buy every morning, this would be known, and their buying pressure would be priced in before the open. Overall, most inventory and intermediary asset pricing models predict that the price should decrease as dealers receive an inventory shock at the close. Price should then gradually increase until the open when dealers expect to unload inventory imbalance. Thus, market returns should be more positive during the entire Asian session to compensate dealers for inventory risk, but returns are zero in the data.

We test the inventory risk hypothesis in several ways. First, inventory risk premium should be increasing in investor risk aversion, but EU-open return does not depend on TED-spread, which measures investor fear and limited capital. Second, as the Asian session became more active: trading costs decreased and volume increased ten-fold, the inventory premium should have decreased over time. However, EU-open returns change little from 2004 to 2018. Finally, suppose that the inability to trade at night matters. While investors can trade continuously during a regular overnight session, the E-mini market is closed for the weekend, from 5:00 pm on Friday to 6:00 pm on Sunday. Thus, according to inventory risk, EU-open returns should be higher on weekends than on weekdays, but if anything the opposite is true.

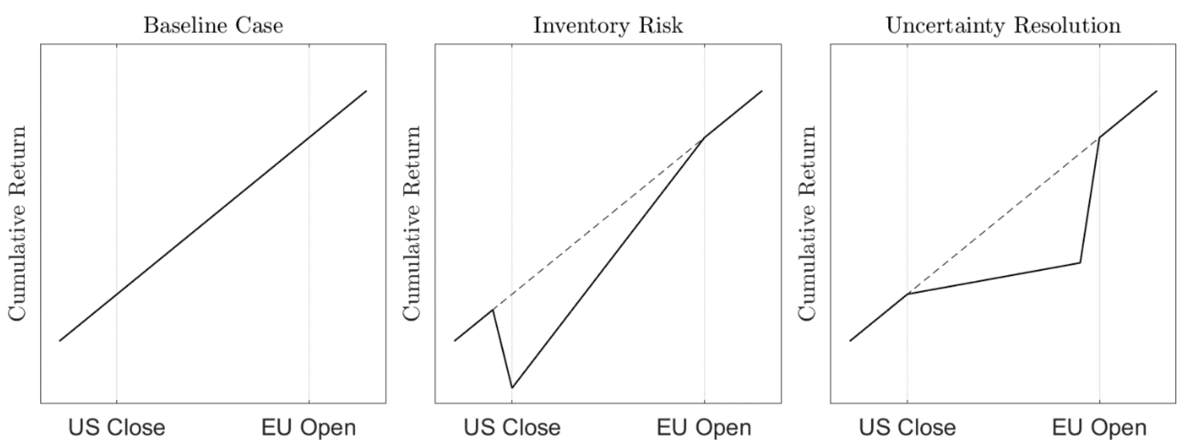

Figure 2. Cumulative market returns that are implied by the main hypotheses. The equity premium is positive constant in the baseline case. For inventory risk, investors require high premium for every overnight hour. For uncertainty resolution, uncertainty discount increases overnight until prices revert to fundamental value at the open.

Stylized graphs in Figure 2 outline the return pattern implied by the main hypotheses. In the baseline case, price increases linearly during the Asian session with constant positive return. Inventory risk implies that price drops as night-averse investors dump positions at the US close and then price increases linearly until investors repurchase their positions at the open. According to the uncertainty resolution, price should underperform the baseline case as uncertainty increases through the Asian session. Then, price should surge/catch up to the baseline at the open as European investors reduce uncertainty and price converges to fundamental value. The return pattern implied by uncertainty resolution is closest to the return pattern in the data.

Our results about the time-of-day seasonality in market returns are related to several literatures. Stroud and Johannes (2014) study how E-mini S&P 500 return volatility depends on time of the day, but they do not study average returns. The literature on day-night returns for individual stocks has a long history. Early evidence is mixed. Wood, McInish, and Ord (1985) report higher overnight returns for six months in 1971/72, while Rogalski (1984) and Harris (1986) find lower returns from 1974 to 1984 and from intraday data for 1983, respectively. Smirlock and Starks (1986) show that overnight returns in the DJIA are lower during the 1974-1983 period and are higher during 1963-1968 and 1968-1974. However, with bigger and better data, a clear pattern emerges. Cliff, Cooper, and Gulen (2008) find that the close-to-open period generates most of the daily return. They hypothesize that "price pressure effects from algorithm generated trading may account for some of the observed price patterns." Alternatively, Berkman, Koch, Tuttle, and Zhang (2012) argue that buying performed by attention-constrained investors drives up the opening price of stocks because of large fluctuations in the prior day, which trigger retail investor attention. In contrast, we show that overnight return is only positive during EU-open, deep night for US investors, and explain the puzlle with uncertainty resolution.[6,7] Also, our results carry important implications for theoretical studies that attempt to explain returns around market closures (e.g., Slezak, 1994,; Longstaff, 1995; Admati and Pfleiderer, 1989; Foster and Viswanathan1990; Hong

[6] A growing literature studies conditional properties of day-night returns. Heston, Korajczyk, and Sadka (2010) show that some stocks tend to perform systematically better than others during specific half hours of the trading day. Lou, Polk, and Skouras (2019) document substantial differences in the cross-section of intraday vs. overnight average returns. They show that some anomalies, such as momentum, earn their premium entirely during the overnight period, while other well-known anomalies, e.g. betting against beta, have a negative premium overnight. Subsequent work confirms and extends their results. Hendershott, Livdan, and Rösch (2020) study day-night CAPM. Bogousslavsky (2019) documents substantial variation in the cross-section of returns within the trading day. Several papers study day-night market return predictability. Akbas, Boehmer, Jiang, and Koch (2020) and Lou, Polk, and Skouras (2020) study how differences in opinion measured by overnight reversal predict future market returns. Gao, Han, Li, and Zhou (2018) show that overnight return for SPY ETF predicts its last half-hour return during regular trading. These studies focus on conditional returns and return cross-section, while we focus on average market return, the main component of the equity premium. Rapach and Zhou (2013) review the market return predictability literature.

[7] In concurrent work, Boyarchenko, Larsen, and Whelan (2020) argue that inventory risk explains positive (negative) market returns during one-hour before the London (after US) open and find that the returns are within the bid-ask spread. In contrast, we study market returns during different intraday intervals and find that the returns are significant net of conservative estimates of trading costs and conclude that the return patterns are most consistent with uncertainty resolution around the EU open.

and Wang, 2000). Our results are also related to other event-based anomalies for market return, such as the pre-FOMC drift.[8] We identify an equally strong and puzzling anomaly. Our results could help distinguish between the theories of the pre-FOMC drift. Finally, Cornett, Schwarz, and Szakmary (1995), Ranaldo (2009), Breedon and Ranaldo (2013) and others study currency returns around the clock, a natural exercise as FX market is open 24/7 and has a unique market structure. The time-of-day return pattern for currencies differs greatly from the equity market.

The paper is organized as follows. Section 2 describes the data and methodology. Section 3 explores how market returns depend on the time of day. Section 4 explores a trading strategy and its after-cost performance. Section 5 discusses potential explanations. Section 6 concludes.

2. Data and methodology

Our initial data for E-mini S&P 500 futures (ticker ES) consist of 10-second bars for trades and quotes obtained from TickData. Trade bars are standard and include open, high, low, and close prices as well as the number of trades and trading volume. Quote bars include closing best bid and best ask, as well as their sizes. Trade data span the period from January 1998 to July 2018. Because TickData only has quote data starting from January 2010, we extend that period to 2006 with similar data obtained directly from CME DataMine.

The notional value of E-mini S&P 500 futures contract is $50 times the value of the S&P 500 stock index, denominated in index points. For example, if S&P 500 is 1566, which is the sample average, then one E-mini S&P 500 contract represents $78,300 worth of exposure. We multiply the number of contracts traded by the contract's notional value to obtain the dollar volume. The contract has four expiration months per year from March quarterly cycle (March, June, September, and December). We use data for the front month contract until it reaches eight days to expiration, at which point we switch into the next available contract. This procedure follows the industry rollover practice and ensures that we use the most actively traded contract throughout our analysis.

Currently, the E-mini contract trades 22:45 hours a day, 5 days a week, with the CME coming online on Sunday at 6:00 pm and closing on Friday at 5:00 pm ET. The continuous trading session spans from 6:00 pm to 4:15 pm the following day (22:15 hours), followed by a 15-minute

[8] Lucca and Moench (2015) and Boguth, Grégoire, and Martineau (2019) among others. Savor and Wilson (2013, 2014) show that average market returns are higher on macroeconomic new announcement days.

trading halt from 4:15 to 4:30 pm and an additional 30-minute trading session (4:30 to 5:00 pm). Our empirical analysis covers the entire 24 hour day including the period from the end of one continuous session (4:15 pm) to the start of the next continuous session. This discontinuous period covers only 1:45 hours during Monday-Thursday, but it lasts for 2 days and 1:45 hours over the weekend and is also longer during holidays.

In our empirical analysis, we exclude days when the market is closed, or when the trading session is cut short due to a US holiday. For most of our tests, we aggregate data to 1-minute or even lower frequencies. We compute one-minute log returns, using the last price for every minute. Log returns can easily be aggregated to any required time horizon by simply adding them up. For easier interpretation, we often annualize average return by multiplying period return by 252, the number of trading days in a typical year. For robustness, we confirm that our results become even stronger if we use simple returns instead of log returns because volatility is much lower during EU-open as compared to the rest of the day. Futures returns offer two practical advantages for studies of equity risk premium: (1) they are already *in excess* of the proper risk-free rate, and (2) unlike for example SPY, they do not require accounting for the dividends paid by S&P 500 index.

Following the literature, we compute the realized volatility from ten-second log returns and then annualize it. The bid-ask spread is the difference between the bid and ask prices. The relative bid-ask spread is the difference between ask and bid price normalized by quote midpoint. Market depth is an average of the number of contracts available at the best bid and best ask. Average bid-ask spread and market depth are computed from ten-second bars.

The E-mini contract history is worth mentioning. The Chicago Board of Trade (CBOT) introduced evening floor trading in the late 1980s to address international demand for Treasury futures during non-US trading hours. However, the strain of trading into the night was more than many traders could handle. Thus, CME Group introduced the Globex concept in 1987 as a "low-impact" means of providing after-hours market coverage. The platform launched on June 25, 1992, running on the technology and network used by Reuters. It began with three currency products and one Treasury note product, but quickly expanded into other assets. Initial volumes were modest, but the system's popularity grew steadily. The E-mini S&P 500 futures contract was introduced on September 9, 1997, after the value of the existing S&P contract became too large for many traders. The contracts are traded electronically on Globex and referred to as "E-mini": "mini" because their size is only 1/5 of that for regular S&P 500 contracts, and "E" because they are only traded electronically. CME instituted an open access policy for Globex in 2000, allowing customers to trade directly in the system, without having to go through a broker. As a result, business soared: In 2002, the Globex average daily volume exceeded one million contracts for the first time, and in 2004, Globex volume exceeded physical pit volume for the first time. This is why we choose to start our sample in 2004.

The E-mini S&P is the most important contract on the S&P 500 index, which is a popular proxy for the market portfolio. Futures are popular in-part because of high embedded leverage and E-mini futures are not an exception. Other alternatives for getting S&P 500 exposure are less popular. The SPDR S&P 500 ETF, or SPY, was launched in 1993 and currently boasts $260B AUM. In 2012, the E-mini S&P contract traded, $142 billion in dollar volume per day versus the $18.5 billion that the SPY trades. SPY can only be traded during normal and extended US exchange trading hours (6:00 am - 8:00pm). Regular, or "big", S&P 500 futures (ticker SP) were popular until early 2000s, but no one trades them currently. Other popular futures contracts, such as E-mini Nasdaq 100 and E-mini DJIA, trade over the same hours that ES futures, but are less liquid outside of US trading hours and have much shorter trading history.

3. Market return around the clock

In this section, we study how market return computed from prices of E-mini S&P 500 futures depend on the time of day. We discover a new stylized fact about average returns, which sheds light on how market returns are formed at the micro level.

3.1 Trading regimes throughout the day: Asia, Europe, and the U.S.

Before we focus on returns, consider how the trading environment changes through the day. A trading day can informally be split into three distinct regimes — Asian (6:00 pm to 2:00 am), European (2:00 am to 9:30 am), and US (9:30 am to 4:15 pm) — which differ in investor composition, news geography, trading activity, and liquidity.[9] The trading technology stays the same, as E-minis are only traded exclusively at GLOBEX. The Asian session is followed by the European session, which is then followed by the US session with some overlap. Table 2 summarizes the trading hours for major international stock markets. A new CME GLOBEX

[9] Throughout the paper, all times are Eastern Time (ET). More precisely, ET is Eastern Standard Time (EST) when daylight saving time (DST) is not observed (winter) and is Eastern Daylight Time (EDT) when DST is observed (summer). When not specified otherwise, all our figures and tables refer to EST season. E.g., Figure 1 corresponds to winter. During summer (EDT), trading hours of Asian (but not European) exchanges would shift by one hour ahead.

session starts at 6:00 pm ET. In winter, Japan opens at 7:00 pm, followed by China and Hong Kong at 8:30 pm. Their stock exchanges remain open until 1:00, 2:00, and 3:00 am, respectively. As expected, during the Asian session, most economic news concerns the Asian region and local investors dominate the session's trading. The European session starts at 2:00 am, when Frankfurt and Eurex open, followed by London and several Euronext markets at 3:00 am. The European session lasts until 9:30 am, when the US stock market opens although most European markets remain open until 11:30 am. Finally, the US session starts at 9:30 am and ends at 4:15 pm, 15 minutes after the US equity market closes. This marks the end of the continuous session. At 4:15 pm, GLOBEX closes for a short technical break, which marks the end of the continuous session. After a 15-minute technical break, there is a 30-minute additional session (4:30-5:00), followed by a 1-hour halt on Monday-Thursday. Then the next trading day begins at 6:00 pm; however, most US investors will have already left by then.

Market conditions differ drastically across these three regimes. Table 3 and Figure 5 show that trading activity and liquidity are expectedly lowest during the Asian session, higher during European hours, while the US session is by far the most active. For example, volatility is 30% lower during the Asian session than during the European segment, which in turn is 50% lower than during the US session. Thus, the entire Asian session only contributes 12% to total daily returns variance and thus is not particularly risky. The difference between sessions is much larger for trading volume. Per-minute volume is 5.5 times lower during the Asian segment in comparison to the Europe session, and per-minute volume during the European session is 8.4 times lower than during the US session. During the Asian session, volume is relatively low compared to volatility because the S&P 500 index value does depend on the Asian economy, but Asian traders are much less important. Trade size, which is another measure of investor clientele, supports this interpretation. The average E-mini trade size is lowest during Asian hours (3.4 contracts). Compared to Asia, the trade size is 44% higher during the European session and 132% higher during the US session. Perhaps, investors who trade E-mini during the Asian session are smaller.

Although the Asian segment is the least active, it is still abundantly liquid in absolute terms: 36 million dollars are traded every minute, or 17 billion dollars during the entire 8-hour Asian session. Thus, even large investors can easily execute their trades. Trading is active: 121 trades are executed every minute on average. The bid-ask spread almost always equals the tick size, which is set to 0.25 index points, or $12.50. In relative terms, one tick corresponds to 0.017% on average during our sample. Because tick size is binding, significant market depth accumulates at the best bid and ask. On average, 65 future contracts sit at the best bid and ask, or about $5.6 million available for immediate execution.

3.2 Average returns around the clock

Figure 1 shows the main result of the paper: how log return for E-mini S&P futures accumulates throughout 24-hour trading day. We annualize cumulative return to make the numbers easier to interpret.[10] It can also be interpreted as an average future price normalized to zero at the origin. Cumulative return remains flat and fluctuates between -1% and 1% annualized over the overnight session. Average price is slightly down (-1.3% p.a.) by 11:30 pm ET, but then the trend reverses. Cumulative return starts increasing slowly at first and then accelerates half an hour before European exchanges (Frankfurt, Amsterdam) open at 2:00 am. The price run-up stops shortly after London opens at 3:00 am. During this remarkable period, cumulative return increases from -1.3% to 6.3% p.a. for a 7.6% total gain. After London open, cumulative return fluctuates between 2% and -2% during the European segment and most of the US session. Surprisingly, volatility bursts at US open and EU close have little effect on average return. The period around US close is interesting. During the last two hours of the US session, cumulative return increases by 4% p.a. This surge during US close is economically large but not statistically significant (Figure 3) due to its huge volatility. Strikingly, this pre-close price increase almost completely reverses between US close at 4:15 pm and market re-open at 6:00 pm, which sees a drop of -2.8%.[11]

Thus, more than 100% of the average market return is concentrated in four hours: between 11:30 pm and 3:30 am ET. We refer to this price run-up period as “EU-open” because 11:30 pm corresponds to 4:30 am German Time, when the first European investors wake up and check the market. Return upward-trend accelerates around 1:30 am (7:30 am in Europe) when many traders arrive to the office half an hour before the start of the European session. Returns continue to increase as London investors check-in. The second half of EU-open accounts for 5.4% of the total return of 7.6% due to main European markets opening during this time. Returns increase steadily

[10] Every day, we normalize the starting price to one at 6:00 pm, when GLOBEX opens for overnight trading, and follow it until 6:00 pm the next day. We compute average log return for average minute across days, and then add up minute returns to compute minute-by-minute cumulative return. Annualized return is period return times 252.
[11] Between 4:15 and 6:00 pm, the market only trades for a short 30-minute session; in the earlier part of the sample, there was no trading during this interval. Hence, we use a single close-to-open return from 4:15 to 6:00 pm and connect the two prices with a straight line in Figure 1.

during EU-open and without zigzags. Figure 3 explores the statistical significance of cumulative returns during EU-open, US close, and the two periods in between by showing minute-by-minute confidence intervals. Of course, the confidence bounds widen with time within each subperiod as volatility accumulates. EU-open cumulative return becomes statistically significant 40 minutes into the period and strongly significant around 1:30 am. US close returns become significant for a brief (20-minute) period around 3:45 pm but then revert and become insignificant.

Table 1 provides main statistics for EU-open return and the rest of the day. Average EU-open return is 7.60% p.a. with a *t*-statistic of 6.35, while return during the rest of the day is -0.8% with a *t*-statistic of -0.17, which is virtually zero.[12] The EU-open period is also less risky according to conventional risk measures. First, its annualized volatility is 4.55%, or 3.9 times lower than for the rest of the day. Skewness is positive (1.64), meaning that large positive returns are more likely than large negative returns, a property that many investors prefer. In contrast, return skewness is negative for the rest of the day (-0.99) and total daily return (-0.42). The largest daily loss is -4.52% for EU-open and -8.47% for the rest of the day. A trading strategy based on EU-open has a maximum drawdown of 8% versus 66.4% for the rest of the day during the financial crisis. Kurtosis is the only measure showing EU-open is riskier, with 57 during the EU-open versus 16 for the rest of the day. Fourth return moments are similar, but EU-open volatility is much lower while kurtosis reflects the ratio of the two. Thus, EU-open is usually quiet but occasionally experiences large price moves. Interestingly, median returns are proportional to time: 2 b.p. (4.7% p.a.) for EU-open and 6 b.p. for the rest of the day. However, skewness plays a major role in determining average returns. In sum, if anything, EU-open appears less risky than the rest of the day, which deepens the return puzzle.

These figures provide visual evidence about which parts of the day are important. We complement them with a moving average analysis that can discover more granular average return patterns. We estimate average return and its *t*-statistic over a one-hour window, then move the window by one minute and repeat. Panel A of Figure 4 shows the resulting centered moving-average *t*-statistic over the day. For the negative return zone, the *t*-statistic touches 5% significance threshold in the hour right before EU-open and in a short period when US macro news is released

[12] Throughout the paper, *t*-statistics account for heteroscedasticity and autocorrelation as in Newey and West (1986). To account for high kurtosis of return distribution, we also compute *t*-statistics with block bootstrap. Our results become even more statistically significant with bootstrapped *t*-statistics. Thus, Newey-West *t*-statistic is more conservative in our case.

at 9:00 am. For positive returns, the moving window t-statistic for average returns reaches six during EU-open while only two other hourly intervals briefly touch a 1% significance threshold: around 7:30 pm and 7:00 am. The US session around 3:00 pm crosses the 5% level but does not reach 1% significance. This figure clearly shows that EU-open stands out massively even during a relatively short time period, like one hour in this case. If the window is extended to a longer period such as four hours in Panel B, EU-open remains the only statistically significant period with a t-statistic greater than six.

For the rest of the paper, we focus on EU-open returns. We assume that expected market return is computed as an average of realized returns. This estimate is often sample-dependent due to high return volatility and time variation in expected returns. However, EU-open returns are extremely robust and consistent. Table 4 reports EU-open returns by year and compares them to the rest of the day. The lowest EU-open returns are 2.25% p.a. and 4.53% in 2017 and 2004, respectively. The highest EU-open returns are 16.24% and 13.52% in 2009 and 2015. Thus, returns are positive and economically significant every year. Average EU-open returns during the first and the second part of the sample match almost exactly. EU-open return volatility follows trends in the overall market volatility and is highest in 2008 and lowest in 2017. In contrast, returns during the rest of the day vary a lot. Returns during the rest of the day are statistically significant in only one year (15.8% with t-statistic of 2.5 in 2017); in contrast, EU-open return is significant in nine out of fifteen years. The lowest return for the rest of the day is, as expected, during 2008 (-55.8%); in contrast, EU-open return is 9.8% in 2008. To study further EU-open returns over time, Figure 6 shows cumulative return and the corresponding t-statistic for a two-year moving average over the sample period. EU-open returns are positive and significant in almost any two-year window. The financial crisis does not affect them apart from higher volatility. In contrast, rest-of-day return is never significant except for two instances when it touches a 5%-significance level in 2014. Thus, average market return is almost never significant outside EU-open, which is as incredible as the consistently high EU-open returns.

Finally, Table 5 reports how EU-open returns depend on the calendar month and day of the week. EU-open return is highest on Tuesdays (9.64%) and lowest on Mondays (4.83%), which corresponds to the weekend. January and October have the lowest EU-open return of 3.11% and 3.75%. Return is highest in December and February: 11.96% and 11.49%. EU-open return volatility is similar during all weekdays and calendar months except for higher volatility in October due to the financial crisis. Overall, EU-open returns are consistently positive and do not vary systematically.[13]

4. Trading strategy

In this section, we explore the after-cost profitability of a trading strategy that exploits EU-open anomaly and buys E-mini futures before EU-open and closes the position at the period's end. We show that this strategy (1) is highly profitable after accounting for conservative estimates of trading costs, (2) has enough capacity to earn fifty million dollars per year, and (3) can be greatly improved by only trading on days with high uncertainty prior to EU-open. This timing strategy has much higher out-of-sample R^2 than that of comparable strategies that predict market return.

The strategy trades twice a day and thus incurs substantial trading costs. We estimate costs conservatively by taking a perspective or a small impatient investor who pays (1) the entire bid-ask spread: half-spread to get in and the other half-spread to close the position and (2) the exchange fees and commissions. The bid-ask spread is almost always one tick, or \$12.5 per contract, with large depth at the best bid and ask.[14] Investors can reduce these costs by providing liquidity with limit orders instead of crossing the spread. Limit orders are filled quickly as 120 trades are executed every minute during the Asian session. We assume that fees and commissions are \$2.50 per roundtrip (/rt) per contract, or 1/5 costs of the tick. Broker commissions are small relative to fees collected by CME. The CME exchange fees for trading E-mini at Globex for non-members increased to \$2.36/rt by the end of the sample period. Our fee estimates are conservative because active investors can reduce exchange fees and commissions to less than \$1.0/rt by owning or leasing a CME member seat.[15]

Panel A of Table 6 reports the profitability of the baseline strategy with and without trading costs. Before costs, the strategy makes a 7.7% annualized return with a Sharpe ratio of 1.65. After

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[13] We also check that our results are robust to excluding (1) days with important macro or earnings announcements, (2) triple witching days, and (3) days when S&P futures hit up/down limits.

[14] We estimate bid and ask prices from trades, which is relatively straightforward as the bid-ask spread is almost always one tick, and many trades execute at bid and ask every instance. We confirm that bid and ask prices implied from trades almost always match actual bid and ask prices for the sample period with available quote data (TickData database provides quotes starting from 2010), and the profitability for strategies computed on trades versus quotes are very similar. We prefer the trade-based bid and ask prices because they rely on actual trades and are available for the entire sample period.

[15] Small hedge funds and prop traders who specialize in E-mini futures often prefer to lease a CME IOM seat for about \$300/month that lowers exchange fees to \$0.55/rt after a volume discount for trading more than 150 contracts a day. The strategy's capacity is about sixty times larger than 150 contracts required for the volume discount. A one-time membership application fee is \$2000.

costs, the profitability expectedly is lower. Average return declines to 2.6% with Sharpe ratio of 0.55. Thus, trading costs reduce profitability by 66%. The return remains statistically significant, and the Sharpe ratio is still reasonably high. This baseline strategy assumes conservative costs and sets an upper bound for the after-cost profitability.

This baseline strategy can be substantially improved. Instead of trading every day, one can trade only on days when expected returns are higher than average. To implement this conditional strategy, we estimate an out-of-sample linear model that predicts EU-open returns. The model only relies on two ex-ante predictors: (1) daily change in VIX (from 4:15 pm to 4:15 pm), and (2) realized volatility during the Asian session before EU-open (from 6:00 pm to 11:30 pm, the start of EU-open). Both predictors are motivated by the uncertainty resolution hypothesis. As we further explain in Section 5.2, when uncertainty is high as measured by positive VIX change or higher Asian volatility, the uncertainty discount is larger during the Asian session leading to higher EU-open returns. Regression coefficients confirm this intuition. We first estimate the model on the first year of data (2004) and then use the estimated coefficients to forecast EU-open returns daily for the next month (1/2005). We then repeat the steps: expand the estimation window by one month, re-estimate the model, and apply it to next month.

This simple predictive model works extremely well. In-line with the uncertainty resolution hypothesis, EU-open return is higher when VIX and the Asian volatility increase. The out-of-sample R^2, or R^2_{OS}, is 6.57% and is stable over the sample period (Figure A.4 in the Appendix).[16] The out-of-sample R^2 is only slightly smaller than the in-sample R^2 of 7.49%. To put this number in perspective, Gao, Han, Li, and Zhou (2018) predict intraday returns for SPY ETF and find an R^2 of 2.6%, "a level that exceeds typical predictive R^2 s at the monthly frequency." After the predictive regressions are estimated, we compute out-of-sample forecasts for EU-open returns and trade only the days when the ex-ante conditional forecast exceeds 1.5 times total transactions costs, and each day is weighed equally. Indeed, it makes no sense to trade on days when costs are higher than expected profits. The conditional strategy trades on 40.2% of days, or about 2 out of 5, and Figure A.4 in the Appendix shows that this fraction is relatively stable through most of the sample. The conditional strategy can be further improved by minimizing trading costs or sizing trades

[16] We compute the out-of-sample R^2 by following the approach of Campbell and Thompson (2008). Intuitively, R^2_{OS} measures the improvement that the predictive model achieves compared to the naïve model, which uses the historical average as the forecast.

proportional to forecasted returns. In sum, the baseline strategy, which is already profitable after-costs, can be easily improved using prior information.

Table 6 shows that the conditional strategy is almost as profitable as the baseline that trades every day. Cumulative annual return for the conditional strategy is 6.7% per year before costs compared to 7.7% for the baseline, despite trading on only 40% of days. Thus, EU-open returns are low on no-trade days (1.07% p.a.). Since the bid-ask spread is almost always one tick, per-trade costs do not change. However, the cumulative costs are lower as we only trade on 2 out of 5 days. Alternatively, the conditional strategy picks days with more than double average return, while trading costs are similar across days. After-cost expected return is 4.61% with a *t*-statistic of 4.6. Its Sharpe ratio is 1.20, only marginally lower than the pre-cost Sharpe ratio for the baseline strategy (1.65). Overall, the conditional strategy is highly profitable even net of trading costs.

How much capital can these strategies accommodate? How do the average returns translate into dollar profits? Acquiring large positions causes price impact that is hard to estimate from the standard public data on individual trades. Nevertheless, even these data can provide useful insights. Practitioners estimate that commercial execution algorithms can trade up to 10% of the average total volume without price impact.[17] This number helps us estimate strategy's capacity. Specifically, we assume that a strategy can buy 10% of observed trading volume during each minute at the ask price. The position is accumulated over a four-hour window: from two hours prior to EU-open at 9:30 pm to 1:30 am, two hours into EU-open. EU-open returns are particularly positive during the second half justifying buying into EU-open. As in a standard VWAP algorithm, we assume that futures are always bought at the ask minute-by-minute executing 10% of recorded trading volume. Similarly, the position is closed by selling futures minute-by-minute at the bid, executing 10% of volume starting at the end of EU-open (3:30 am). The position can be usually closed within an hour due to higher volume during the European session. Subject to these simplifying assumptions, we evaluate trade capacity for the baseline and conditional strategies before and after costs. In practice, risk-managers enforce limits on traders' positions. Thus, we consider two variations of the strategy: (1) unconstrained, and (2) constrained. The constrained strategy limits maximum position size to 30% of the median volume during accumulation window over the trailing two months. A few days with extremely high volume, such as the U.S. Election night (11/09/2016) or the night after "Volmageddon" (02/06/2018), skew volume distribution. Our

[17] For example, see ITG (2015) and MSCI (2019) "Liquidity Metrics" report.

strategies take large positions and perform well on high volume days. Thus, without risk limits, those few influential days would contribute disproportionally to profitability. We prefer a more conservative constrained strategy.

Panels B and C of Table 6 report results for unconstrained and constrained strategy variations. We only discuss results for the constrained strategy that is more conservative. The conditional strategy often trades on high volatility and volume days, and thus it typically acquires a larger position than the baseline strategy: $9.3 billion of S&P 500 exposure versus $6.9 billion, which is accumulated during the four-hour window. These estimates indicate that investors can deploy significant capital into these strategies. EU-open strategy has no analogs, but its capacity seems comparable to size, value, and momentum anomalies in US equities that have break-even market-wide capacities of $18.2, $9.4, and $5.2 billion, respectively, according to Frazzini, Moskowitz, and Israel (2012). Despite large costs, the EU-open strategies earn large profits net of trading costs. The baseline strategy earns before and after-cost annual profits of $80 and $40 million, respectively, while the conditional strategy earns $60 and $50 million pre- and post-costs. The unconstrained version of the strategy earns three times higher annual profits. These back-of-the-envelope estimates are a useful starting point for evaluating tradability of the EU-open puzzle.

Finally, even long-term investors can benefit from high EU-open returns. Obviously, they cannot utilize the high-turnover daily buy/sell strategy. However, the EU-open puzzle should affect the timing of their trades. If a long-term investor wants to buy or sell a future, the time period before or after EU-open will be the most optimal. This way investors benefit from high EU-open return as they are not compensated for holding market risk during the rest of the day.

5. Explaining the puzzle

In this section, we consider several explanations for the EU-open puzzle. Alternative explanations imply different return patterns. Conventional risk theories imply that expected returns should be proportional to risk and thus positive in all intraday intervals. Perhaps, expected return is constant and positive in calendar time or in volatility time, which corresponds to constant Sharpe ratio. We compare other theories against this baseline. We focus on two most promising hypotheses: inventory risk and uncertainty resolution. Figure 2 scratches return patterns implied by the three main hypotheses. In the baseline case (Panel A), the price increases linearly during the Asian trading session (i.e., constant positive return). Inventory risk implies that the price drops as night-averse investors dump their positions at the US close and then price increases linearly until investors repurchase their positions at the EU open (Panel B). According to uncertainty resolution (Panel C), price underperforms the baseline case as uncertainty increases through the Asian session and then the price increases/catches up at the open as European investors reduce uncertainty by aligning price with fundamental value. The return pattern for uncertainty resolution is closest to returns observed in the data.

5.1 Asian close versus European open

To understand why EU-open returns are high, we first disentangle the impact of two main recurrent events during this period: European markets open (Frankfurt and then London) and Asian markets close. Intuitively, the Asian session is less active, and thus Asian close is less likely to affect EU-open returns. The challenge is that China closes at 2:00 am exactly when Frankfurt opens. Similarly, London opens and Hong Kong closes at 3:00 am. Table 2 summarizes open and closing times for major equity markets. We separate the effects of Asian close and European open by using daylight saving time (DST) as an exogenous shock to relative time between Europe and Asia. Asia does not observe DST, while Europe and the US do. DST in US extends from the second Sunday in March to the first Sunday in November. DST in Europe extends from the last Sunday in March to the last Sunday in October. Thus, DST in Europe and the US overlap except for a brief period of three or four weeks, depending on a specific calendar year.

Thus, from the US perspective, Hong Kong market closes at 3:00 am ET in winter but at 2:00 am in summer. If Asia is important, the EU-open price run-up will shift with the shift in Asian time relative to Europe/US. Figure 7 tests this hypothesis by comparing cumulative returns and trading volume around EU-open during winter and summer DST periods in Europe. In European time, cumulative returns and volume are remarkably similar for the two subperiods as shown in the top panel of the figure. Thus, the EU-open return pattern is constant in European time and thus shifts in Asian time. Indeed, when the same graphs are presented in Asian time in the two lower panels of Figure 7, you can clearly see a one-hour shift between summer and winter return and volume. The fact that volume pattern “lives” in European time is not surprising as European session is more liquid than the Asian session. This shift in the cumulative return confirms that European open and not Asian close drives the EU-open price run up.

5.2 Uncertainty resolution and VIX

Uncertainty resolution hypothesis comes closest to explaining the EU-open puzzle. In short, European investors return to the market after the night break during EU-open, they process accumulated information, and thus resolve uncertainty, which in turn increases prices.

Because uncertainty resolution is less well-known than inventory risk, we first explain this mechanism before applying it to the EU-open puzzle. By price uncertainty we mean that market prices deviate from fundamental value, the unobserved price that would reflect all public information after a proper risk-adjustment. Prices can deviate from fundamental value as public information is not fully processed. For example, an annual report contains an ocean of price-moving data that are impossible to interpret fully. By analogy, physics laws imply that an engine cannot transform energy into useful work at 100% efficiency. Also, investors can differ in their processing ability and capacity. Price uncertainty can be quantified as a standard deviation between fundamental value and market price. Thus, price can randomly deviate from fundamental value with zero average difference. Uncertainty measures how far price can be from fundamental value.

Uncertainty is priced because investors rely on prices to choose their portfolios and make other investment decisions. Higher uncertainty makes an asset riskier as its price is further away from value, but investors cannot tell whether the asset is overvalued or undervalued. Thus, investors will require a price discount. Hu et al. (2019) formalize this intuition with a stylized model. In their three-period model, a final payoff is paid in the last period and has a random variance. The value for the variance is revealed in the second period, hence uncertainty resolution. They show that when uncertainty is being resolved not only do prices increase but volatility can stay relatively low. Relatedly, Easley and O'Hara (2004) study how total amount of information in the system affects asset prices. They show that a lower fraction of informed traders makes the stock riskier for both informed and uninformed investors increasing expected return. Expected return increases because when information is private, rather than public, uninformed investors cannot perfectly infer information from prices, and consequently they require higher return. In both theories, the more information (through public or private signals) prices reflect the smaller is the price discount relative to fundamental value. These related theories help us understand how uncertainty resolution around EU-open can produce observed returns. If investors know that important information is withheld from the market, prices will be lower to reflect the risk of large price changes after the information becomes public.

During US and European sessions, many sophisticated investors are active and keep prices reasonably close to fundamental value. However, uncertainty can accumulate during the Asian session as fewer investors are active and differ in their ability to interpret public information. The most informed investors sleep and thus quit the market during the Asian session. Uncertainty is resolved during EU-open. Large European investors wake up, arrive to the market, and push E-mini price towards fundamental value. European investors do not necessarily have private information; they just collectively better interpret public news from the Asian session, which includes any price relevant information. Alternatively, imagine that each investor receives a small private independent signal about fundamental value during the Asian session. Asian investors trade on their signals right away, while EU investors, who account for a majority of signals, trade after waking up during EU-open. EU-returns are positive since uncertainty decreases as all signals are priced in. Individual signals are small and independent enough so that costs of waking up at night overweigh the benefits for EU investors.

The following six independent tests support the uncertainty resolution explanation. *First*, the last panel in Figure 5 shows that trade size starts to increase right at the start of EU-open and keeps increasing through the period indicating that European investors indeed return to the market during EU-open. *Second*, EU-open return should increase proportional to resolved price uncertainty. Trading volume and realized volatility reflect the amount of released public information and thus capture price uncertainty during the Asian regime. As predicted by the hypothesis, Table 7 shows that EU-open returns are higher when volatility or volume are high during the Asian session before EU-open, but returns are not significantly related to volatility or volume of the preceding US session. For example, Asian volume has a t-statistic of 3.3 versus 1.3 for the US session volume. In these regressions, we estimate volatility as realized volatility from ten-secondt returns as well as absolute return over the entire period; volume is estimated as the number of futures contracts traded. Volume and volatility are then normalized by its two-week trailing average to account for changes in aggregate market conditions.

Third, a variance ratio test shows that prices are less efficient during the Asian session compared to the rest of the day. A variance ratio is higher before EU-open than after EU-open. Specifically, variance at time t is computed as average over all days of squared returns from t to $t+24h$. Figure 10 reports a ratio of variance at time t to overall daily average variance for all starting times. Variance ratio at the start of EU-open is 1.08, or 8% higher than average, by the end of EU-open it drops to 0.95. Thus, as measured by variance ratio, price efficiency decreased by 12%, suggesting that pre-EU-open prices contain more noise.

What if European investors are absent from the market during EU-open perhaps because they are on holiday? EU holidays provide a quasi-exogenous shock that turns down the uncertainty resolution during EU-open. The theory predicts that if uncertainty is not being resolved, EU-open returns will be zero rather than positive, and instead positive returns will shift to later in the day. We confirm this prediction. We obtain holiday dates from the New York Times website and focus on days when the two main European exchanges, Frankfurt and London, are closed, but US market (and thus CME) is open. The list includes both recurrent holidays, such as National day in Germany or the Summer bank holiday in the UK, and special occasions, such as the Royal Wedding celebration. There are 81 such holidays in total during our sample period. Table 8 compares average returns and trading activity for holidays with the rest of the sample. Confirming lack of uncertainty resolution during EU-open on EU holidays, E-mini futures volume and volatility drop by 54% and 19%, respectively, relative to the previous month average. Strikingly, EU-open returns are slightly *negative* on EU holidays (-0.5% p.a.), but returns are positive during the rest of the European session: 9.5% p.a., which is comparable to the average EU-open return on non-holidays. Perhaps, uncertainty resolution and positive returns associated with it shift to when first US investors arrive later in the day.

Fifth, our most direct evidence to support the uncertainty resolution hypothesis comes from VIX index and VIX futures. VIX is commonly used as an uncertainty measure. For example, Ederington and Lee (1996) and Beber and Brandt (2006) show that the uncertainty measured by implied volatility from options on Treasuries drops substantially after the release of macroeconomic news. Hu et al. (2019) use positive shocks to VIX to study uncertainty resolution around FOMC announcements. We first show that when uncertainty is high, as measured by VIX (at 4:15 pm) or its daily change (from 4:15 pm to 4:15 pm), EU-open return is more positive. The last column of Table 7 reports that VIX level is the only significant macro predictor of EU-open return (t-statistic of 2.2). If both VIX level and change are included, VIX change is highly significant with t-statistic of 4.1 and VIX level loses significance (t-statistic of 1.2).

Ideally, we would like to observe VIX changes, which proxy for changes in uncertainty, during the Asian session and EU-open. Unfortunately, VIX is computed from S&P 500 index option prices, which do not trade during EU-open. However, we can use VIX futures (ticker VX), the only VIX-linked product that actively trades overnight. VIX futures were introduced by CBOE Futures Exchange (CFE) on March 26, 2004, but average daily volume only crossed the 10,000 mark in 2010 and surpassed 300,000 contracts in 2017. On June 22, 2014, CFE finally extended VIX futures trading hours to match E-mini futures, or nearly 24 hours a day. Thus, VIX futures traded during the Asian session and EU-open for only four years. Otherwise, we follow the same methodology as for E-mini S&P futures.

Figure 11 and Table 9 show how VIX futures returns depend on time of day. Strikingly, VIX returns are positive during the Asian session before EU-open with annualized cumulative return of 37.5% and *t*-statistic of 2.7. Cumulative return steadily increases except for a drop during China/Hong Kong open at 8:00 pm ET. This drop is consistent with uncertainty building up during the overnight session and then being partially resolved by the Asian open. During EU-open, cumulative VIX return starts to decrease and quickly becomes negative. Cumulative VIX return during EU-open is -46.2% (*t*-statistic of -5.2). Thus, uncertainty decreases during EU-open and especially its second part, when European markets officially open. During EU-open, uncertainty as measured by VIX decreases, while market returns are positive – a direct prediction of the uncertainty resolution hypothesis. VIX return varies wildly during the rest of the day but is not statistically significant except for a short period around US close. Bottom panel of Figure 11 confirms these results. Out of any four-hour window during a day, (1) only period before EU-open has positive VIX returns, (2) only during EU-Open, VIX returns are negative and significant at the 1% level, and (3) VIX returns are mildly negative but rarely significant during the rest of the day. Figure 12 confirms that these results hold through the entire sample period by showing a two-year moving average for VIX returns are the corresponding *t*-statistic. EU-open VIX returns are negative and significant at the 1% level in any two-year period.

Finally, we show how returns respond to changes in the speed at which uncertainty is being resolved. Table A.4 in the Appendix shows that uncertainty is being resolved faster during the second half of EU-open. Indeed, VIX futures returns are more negative in the second half than: -41.7% versus -4.6% in the first half. The theory predicts that market returns should be more positive in the second half, which is true: 5.9% versus 1.7%. Intuitively, as uncertainty resolution accelerates, we should also observe higher trading volume and volatility. Indeed, volatility increases from 0.11 in the first half to 0.15 in the second half. Similarly, volume increases from 37.7 to 132.2 thousand contracts.

5.3 Inventory risk

What if many investors are averse to the overnight period and avoid it by hedging or not carrying positions during the Asian session? If so, such investors have to pay a premium to liquidity providers, who take this risk. Inventory risk (or intermediary capital) arises because liquidity providers are risk-averse and have limited capital. Dealers are required to accommodate customer order flow and thus hold suboptimal portfolios. Hence, they require compensation for holding this inventory risk, which increases in undesired position size, asset volatility, dealer's risk aversion, and expected holding period. Perhaps, some European investors fear avoid holding positions overnight by selling at the US close and re-open their positions at the open. Alternatively, investors can hedge equity positions by selling E-mini futures overnight and thus keep zero beta during the undesirable period. Intuitively, their price pressure would decrease prices around the close until prices rebound around the open. This price rebound can coincide with EU-open. Thus, inventory risk hypothesis argues that EU-open returns are high because night-averse investors re-open their positions around European open and their order flow pushes prices higher.

Inventory risk seems intuitive and plausible; however, on closer inspection, this hypothesis faces numerous challenges in explaining EU-open returns. The pattern implied by the theory just does not line up with the data. We next carefully evaluate each implication of inventory risk hypothesis one-by-one. First, hedging overnight risk requires daily trading, and trading costs quickly add up and make such hedging prohibitively expensive. The average bid-ask spread is 1.7 bps while the entire average market return is 3.8 bps per day, thus the spread consumes almost half of the return. Commissions and exchange fees further increase the costs.

Maybe inventory risk is priced because the Asian session is highly illiquid, and investors must wait until European open to adjust their position. If investors want to adjust positions, then waiting until EU-open is a waste of time. With an average volume of 2.4 billion dollars per hour (pre-EU-open), the Asian session is certainly liquid enough to accommodate large trades. Waiting until EU-open does not reduce trading costs as the bid-ask spread is always one tick regardless of time of day. E-mini market is fully electronic and trade execution can be easily automated either in-house or using broker-supplied algorithms that are available even to retail investors.

We directly test whether the inability to trade during the Asian session or its perceived illiquidity affect cumulative returns during Asia and EU-open. First, while investors can trade continuously during a regular overnight session, the E-mini market is closed for most of the weekend: from 4:15 pm on Friday to 6:00 pm on Sunday. Thus, premium for inventory risk should be larger over weekends than on weekday nights. Figure 8 compares cumulative return and trading volume over a day on weekdays compared to weekends. Trading volume is essentially identical for the two samples, except for higher volume during the first two hours of weekend trading when information accumulated from Friday close to Sunday open is being priced. Trajectories for cumulative returns are also remarkably similar. Weekend returns are noisier because the sample size is four times smaller than for weekdays. For weekends, cumulative return increases from 0.4% to 5.6% during the EU-open, while it increases from -1.6% to 6.6% for weekdays. Thus, if anything weekend returns are lower than on other days, and the difference is marginally significant (*t*-statistic of 2.3). This test's results are not consistent with the hypothesis that non-trading periods carry higher premium.

Next, we test whether night illiquidity leads to high inventory risk premium by comparing the first and second parts of the sample, as liquidity during the Asian session increased substantially. Figure 9 shows that while trading volume remained unchanged during the US session, it doubled during European session and quadrupled during the Asian session. Overnight liquidity clearly improved considerably. However, cumulative returns are identical though the entire trading day until the US open. Returns diverge during the US session due to the financial crisis in the per-2011 period. Thus, night liquidity does not affect EU-open return even though it should according to the inventory risk hypothesis.

Why are investors so scared of the overnight period and specifically the Asian session? It is not clear, as this session is least risky (compared to Europe and US) as measured by conventional measures. Ten hours between the US close and European open represent only one-tenth of total return variance and contain fewer important news than other periods. Leaving for a long lunch in the middle of the US trading session is almost as risky as the entire Asian session. Figure A.1 in the Appendix confirms this point by showing cumulative return in calendar time and in variance time. The Asian period before EU-open contributes 10% to the variance, EU-open contributes another 8%. In contrast, 6.75 hours of the US trading day contributes 60%.

If prices rebound so strongly around EU-open, then an equally large price drop should be around European or U.S close, but we do not see it in Figures 1, 3 or 4. If anything returns are more positive around US close, and cumulative return for the day increases from 6% to 10% between 2:00 pm and 4:15 pm, when the US market closes. Returns are highly volatile during this period. Also, in the extended sample, we find that returns are massively negative around the US open during the burst of the dot-com bubble in 2001-2002. We attribute these returns to margin selling by US investors.

A more fundamental challenge is why dealers receive compensation only during EU-open but not during the rest of the night (the Asian session before EU-open), which contradicts inventory models. Not only are dealers not compensated for holding inventory overnight, they lose money as cumulative return is slightly negative (-1.5% p.a.) in the pre-EU-open period. Maybe dealers are compensated at EU-open, but an opportunistic investor (who carries no inventory risk) can earn the same EU-open return by "cutting the line" and buying right before EU-open. We show in Section 4 that this strategy is profitable after costs. The free rider can boost returns by buying at the bid as he or she loses nothing if the limit order is not executed.

Finally, any expected inventory change/order imbalance must be reflected in prices in advance. If European investors buy every morning at the open, this would be known, and their buying anticipated pressure would be reflected in prices hours before the open. Similarly, only unexpected selling lowers prices. The observed return pattern with high EU-open return and no significant corresponding drop in price is consistent with EU-open buying pressure being unexpected and corresponding selling being anticipated. Additional tests show mixed results. First, compensation for inventory risk should be proportional to expected volatility, EU-open returns are indeed increasing in VIX level and its innovations. But the uncertainty resolution hypothesis has a similar prediction. Second, EU-open returns do not depend on TED spread, which is a popular measure of investor fear/risk aversion and limited capital.

Overall, most inventory and intermediary asset pricing models predict that the price should fall as dealers receive an inventory shock at the close, the price should then gradually increase until the open as dealers expect to unload inventory imbalance at the open. Thus, market return should be higher (more positive) during the entire Asian session to compensate dealers for holding inventory risk. This predicted return pattern is completely different from the one observed in the data. In Figure 1, price remains flat or decreases slightly during the Asian session and then increases rapidly during EU-open.

5.4 Other explanations

Conventional risk-based theories attribute expected returns to higher risk as reflected by systematic volatility, price jumps, and negative skewness, among other measures. But these risk measures are lower during EU-open compared to the rest of the day. Also, EU-open does not contain important macro news. European macro announcements are at or after 3:30 am, which is the end of EU-open.

An investor sentiment hypothesis argues that European investors are buying at the open because they are more optimistic than everyone else. We test this hypothesis by studying how EU-open return depends on measures of investor sentiment including the bull-bear sentiment from the AAII investor survey (proxy for the sentiment of US retail investor), Baker and Wurgler (2006) index (proxy for institutional investor sentiment), the University of Michigan consumer confidence, and the TED spread. None of them significantly predict EU-open returns in Table 7 except for Michigan consumer sentiment that is significant at the 10% level.

Carry costs including different interest/margin payments and security lending fees are typically incurred after market close. Market return should be higher during the night period when these costs are incurred to compensate investors for the costs. It is not clear that any of these costs are concentrated in EU-open, but we still test this hypothesis. Carry costs are usually proportional to the level of interest rates, but last column of Table 7 shows that EU-open returns are uncorrelated with interest rates. Also, most carry costs are incurred every calendar day and thus are higher over weekends, but EU-open returns are slightly lower over weekends, although the difference is not statistically significant. We conclude that sentiment and direct carry costs are unlikely to explain the EU-open puzzle.

Algorithmic trading and high-frequency trading (HFT) have been extensively adopted during our sample period and could be responsible for some of the return patterns. Although we do not observe which trades are initiated by algorithms, the fact that EU-open returns changed little over the sample period suggests that the growth of algorithmic trading and HFT does not substantially impact EU-open returns.

6. Conclusion

In this paper, we introduce a new puzzle about average excess market return. E-mini S&P futures are actively traded almost 24/5, and we use their prices to study how excess return for S&P 500 index depend on the time of day. One period clearly stands out. All the average market return is concentrated in just four hours between 11:30 pm and 3:30 am ET, which corresponds to deep night in the US and early morning in Europe. Return is particularly high in the second half of this period, when European markets start to open. EU-open return is highly statistically significant, and the price steadily increases during this period. In contrast, average return during any other four-hour period is zero or slightly negative. EU-open has low risk according to conventional measures. High return combined with low risk leads to an impressive Sharpe ratio. The EU-open return pattern is extremely robust and is observed in every year, calendar month, and weekday. We also show that a strategy of buying/selling futures before/after EU-open is profitable net of conservative estimates of trading costs and has a high capacity. Using daylight savings time as an exogenous shock to relative time between Europe and Asia, we show that EU-open return is driven by the European open rather than the Asian close.

We propose and test several potential explanations. One of them, uncertainty resolution, is particularly promising. As new information arrives to the market, investors quickly process it and update prices through trading. Thus, prices are normally close to fundamental value. However, during the Asian session, most investors sleep and thus do not participate in information processing. As a result, information uncertainty accumulates through the Asian session, as prices can further deviate from fundamental value because incoming information is not fully processed. As European investors wake up and process the accumulated information, uncertainty is resolved, and prices increase. Several tests, most notably EU holidays and VIX future returns, support this theory.

Taken at face value, these results imply that uncertainty resolution arises naturally in financial markets and is a critical determinant of the average market return. Thus, a natural next step would be to study the relation between average returns and uncertainty in other contexts. Overall, information uncertainty could play a more prominent role in asset pricing than is currently assumed.

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Table 1
Returns during EU-open and the rest of the day

This table reports main statistics for E-mini S&P futures returns, including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average return during EU-open is 7.60% annualized. Also reported are return distribution percentiles, which are not annualized. E.g., the minimum return during EU-open is -3.97%. The entire trading day in the last column is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance only using the same subperiod, such as EU-open.

	EU-open	Rest of the day	Entire day
Average return, % p.a.	7.60	-0.80	6.80
t-statistic	6.35	-0.17	1.39
Standard deviation, %	4.55	17.79	18.63
Sharpe ratio, p.a.	1.67	-0.05	0.36
Skewness	1.64	-0.99	-0.42
Kurtosis	56.96	15.77	16.80
Min, %	-3.95	-13.07	-12.01
5%	-0.32	-1.77	-1.73
25%	-0.08	-0.41	-0.39
50%	0.02	0.06	0.08
75%	0.13	0.52	0.54
95%	0.41	1.47	1.57
Max, %	4.52	8.47	11.28
Max drawdown, %	7.96	66.40	61.89

Table 2
Trading hours for major equity markets
This table reports trading hours and lunch break time, if applicable, for major equity markets. Hours are reported in local time zone and Eastern Time. Daylight Savings Time (DST) in Europe extends from the last Sunday in March to the last Sunday in October; DST in US extends from the second Sunday in March to the first Sunday in in November. Additional exchanges that open at 2:00 ET: Moscow, Johannesburg, Tel-Aviv, Saudi, Bursa Istanbul; at 3:00 ET: Euronext (Amsterdam, Brussels, Lisbon, London), Swiss, Spanish, Milan, Stockholm: and at 9:30 ET: Toronto, Mexico.

Stock Exchange	RTH (Local Time)	RTH (EST)	Lunch (EST)	DST
Japan	9:00–15:00	19:00–1:00	21:30-22:30	None
Shaghai, Shenzhen	9:30–15:00	20:30–2:00	22:30-23:30	None
Hong Kong	9:30–16:00	20:30–3:00	23:00-0:00	None
Frankfurt	8:00–20:00	2:00–14:00	None	Mar–Oct
Eurex	8:00–22:00	2:00–16:00	None	Mar–Oct
London	8:00–16:30	3:00–11:30	None	Mar–Oct
Euronext (Paris)	9:00–17:30	3:00–11:30	None	Mar–Oct
NYSE, NASDAQ	9:30–16:00	9:30–16:00	None	Mar–Nov

Table 3
Trading activity during a trading day
This table reports averages for several trading activity and liquidity measures for E-mini S&P 500 futures for selected intraday intervals. The entire trading day (last column) represents the daily continuous session (6:00 pm to 4:15 pm) and is split into Asia pre EU-open (6:00 to 11:30 pm), EU-open (11:30 pm to 3:30 am), Asia (6:00 pm to 2:00 am), Europe (2:00 am to 9:30 am), US (9:30 am to 4:15pm). The measures include trading volume, number of trades, trade size, the bid-ask spread, and the market depth. Measures are reported per minute and as period totals. The bid-ask spread is almost always one tick ($12.50). The relative bid-ask spread is the difference between bid and ask prices normalized by the midquote and is reported in basis points. Market Depth = 0.5 × (Best Bid Size + Best Ask Size). The statistics for the bid-ask spread and market depth are based on the subsample with available quote data from 2006 to July 2018. S&P 500 index average is 1634 during this subperiod and is 1566 during the full sample from 2004 to July 2018.

	EU-open	Asia pre EU-open	Asia	Europe	US	Entire day
Length, hours	4	5.5	8	7.5	6.75	22.25
Volatility, annualized	0.16	0.15	0.14	0.20	0.32	0.23
Volume, per minute, contracts	708	475	429	2341	20128	7050
Volume, per minute, $M	58	40	36	183	1535	540
Volume, total, $B	14	13	17	82	622	721
Number of Trades, per minute	195	131	121	547	3159	1186
Number of Trades, total, 000s	47	43	58	246	1279	1584
Average Trade Size, contracts	3.7	3.5	3.4	4.9	8.0	5.3
Bid-Ask Spread, ticks	1.034	1.035	1.036	1.021	1.005	1.022
Bid-Ask Spread, bp	1.71	1.71	1.71	1.71	1.69	1.70
Market Depth, contracts	73.7	65.6	64.6	133.5	442.4	202.4
Market Depth, $M	6.2	5.6	5.5	10.8	34.3	16.0

Table 4
Returns by year

This table reports main statistics for E-mini S&P futures returns by year. The statistics include average return, standard deviation, and *t*-statistics. All these statistics are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average return during EU-open in 2004 is 4.53% annualized. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistics is computed to account for heteroskedasticity and autocorrelation. Last row reports sample average.

	EU-open			Rest of the day		
	Average return, %	Std. dev., %	*t*-stat.	Average return, %	Std. dev., %	*t*-stat.
2004	4.53	2.20	2.06	4.53	11.05	0.41
2005	7.12	1.86	3.83	-5.77	10.40	-0.56
2006	5.71	2.05	2.78	4.81	9.95	0.48
2007	6.96	2.96	2.34	-8.63	15.66	-0.55
2008	9.80	10.41	0.94	-55.82	39.25	-1.42
2009	16.24	5.81	2.79	4.19	24.89	0.17
2010	5.60	4.70	1.19	8.37	18.43	0.45
2011	8.85	6.76	1.31	-5.52	23.36	-0.24
2012	6.40	3.08	2.06	9.09	14.35	0.63
2013	6.06	2.66	2.27	18.36	10.85	1.69
2014	5.66	2.21	2.55	7.54	11.05	0.68
2015	13.52	3.38	4.00	-12.89	15.05	-0.86
2016	5.38	4.33	1.24	5.71	12.43	0.46
2017	2.25	1.38	1.63	15.83	6.29	2.51
2018	11.47	5.64	1.55	-2.50	14.97	-0.13
Total	7.60	4.55	6.35	-0.80	17.79	-0.17

Table 5
Returns by weekday and calendar month

This table reports main statistics for E-mini S&P futures returns by day of week (Panel A) and by calendar month (Panel B), including average return, *t*-statistics, standard deviation, and Sharpe ratio. They are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. E.g., the average EU-open return on Monday is 4.83% annualized. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am ET) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Last row reports sample average.

Panel A

	EU-open				Rest of the day			
	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.
Monday	4.83	4.87	0.99	1.63	-4.68	18.62	-0.25	-0.41
Tuesday	9.64	5.77	1.67	2.79	10.29	17.07	0.60	1.04
Wednesday	8.72	3.97	2.20	3.83	-0.68	18.68	-0.04	-0.06
Thursday	8.51	3.91	2.17	3.71	-0.33	17.95	-0.02	-0.03
Friday	6.02	3.97	1.52	2.61	-9.16	16.59	-0.55	-0.94

Panel B

	EU-open				Rest of the day			
	Average return	Std. dev.	Sharpe ratio	*t*-stat.	Average Return	Std. dev.	Sharpe ratio	*t*-stat.
January	3.11	4.06	0.77	0.83	-17.72	17.19	-1.03	-1.12
February	11.49	4.96	2.32	2.48	-5.63	16.43	-0.34	-0.37
March	10.59	3.39	3.13	3.57	5.86	17.03	0.34	0.39
April	7.06	3.14	2.25	2.49	12.60	14.07	0.90	0.99
May	4.86	3.67	1.33	1.49	-0.12	14.34	-0.01	-0.01
June	9.53	3.38	2.82	3.18	-19.72	15.50	-1.27	-1.44
July	5.71	3.26	1.76	1.96	14.31	14.01	1.02	1.14
August	8.26	5.56	1.49	1.65	-14.18	17.97	-0.79	-0.87
September	7.87	4.08	1.93	2.06	-4.78	19.06	-0.25	-0.27
October	3.75	8.28	0.45	0.50	3.90	24.90	0.16	0.17
November	7.11	5.00	1.42	1.52	7.25	22.34	0.32	0.35
December	11.96	3.40	3.52	3.78	8.52	18.04	0.47	0.51

Table 6
Trading strategy
Panel A reports profitability of a trading strategy that buys E-mini futures at the start of EU-open and sells them at the end of EU-open, with and without transaction costs ("TC"). We report annualized average return, standard deviation, Sharpe ratio, and *t*-statistic. The baseline strategy trades every day, while the conditional strategy trades on about 40% of days with higher expected EU-return as predicted by an out-of-sample linear model with daily change in VIX and Asian volatility. The transaction costs include paying the full bid-ask spread and exchange fees/commissions. Panels B and C also report annual dollar profits (P&L) and average position on a typical day a strategy trade. The strategy accumulates positions during a four-hour window by buying 10% of trading volume at the ask minute-by-minute. The accumulation window from two hours before to two hours into EU-open (9:30 pm to 1:30 am). Similarly, the position is liquidated by selling 10% of minute-by-minute volume at the bid, which usually takes less than an hour.

Panel A. Strategy without accumulation window

Strategy	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.
Baseline, no TC, %	7.76	4.72	1.65	6.27
Baseline, with TC, %	2.58	4.71	0.55	2.09
Conditional, no TC, %	6.69	3.86	1.73	6.60
Conditional, with TC, %	4.61	3.84	1.20	4.57

Panel B. Strategy without constraints, four-hour accumulation window

Strategy	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.	P&L, $M p.a.	Position size, $B
Baseline, no TC, %	6.76	4.48	1.51	5.75	200	7.41
Baseline, with TC, %	1.48	4.48	0.33	1.26	170	7.41
Conditional, no TC, %	5.37	3.58	1.50	5.71	190	10.52
Conditional, with TC, %	3.42	3.56	0.96	3.66	170	10.52

Panel C. Strategy with position constraints, four-hour accumulation window

Strategy	Average return, %	Std. dev., %	Sharpe ratio	*t*-stat.	P&L, $M p.a.	Position size, $B
Baseline, no TC, %	6.52	4.56	1.43	5.44	80	6.92
Baseline, with TC, %	1.24	4.56	0.27	1.03	40	6.92
Conditional, no TC, %	5.08	3.67	1.38	5.27	60	9.29
Conditional, with TC, %	3.13	3.65	0.86	3.27	50	9.29

Table 7
Conditional EU-open returns
This table shows how market returns during EU-open depend on lagged market conditions. For the columns marked (1) through (4), we focus on short-term predictors based on the Asian session before EU-open and previous US session. We include VIX index (implied volatility for one-month SPX options) and its change from previous close. We also include shocks to log volume, absolute returns, and volatility during these two periods. In column (5), we show how EU-open return depends on macro variables measured at the previous close: VIX index, short-term Treasury rate, term spread (difference between long-term and short-term rates), TED spread (difference between on-month LIBOR and Treasury rates), bull-bear spread from AAII Investor Sentiment Survey (mood of US individual investors), Baker and Wurgler (2006) sentiment, University of Michigan Consumer Sentiment Index (US consumer confidence), and a weekend indicator. Standard errors are adjusted for autocorrelation and heterogeneity.

						EU-open Ret
	(1)	(2)	(3)	(4)		(5)
VIX change	0.0970***				VIX	0.0168**
	[4.1]					[2.2]
VIX	0.0054				Treasury Rate (1m)	0.0079
	[1.2]					[0.8]
Volume, Asia		0.1282***			Term Spread	0.0076
		[3.3]				[0.4]
Volume, US		0.0714			TED Spread	-0.1518
		[1.3]				[-1.6]
|Ret|, Asia			0.1676**		Retail Invest Sent	-0.0836
			[2.6]			[-0.7]
|Ret|, US			0.0204		BW Sent	0.1534
			[1.2]			[1.2]
Volatility, Asia				0.3660***	UMich. Cons Sent	0.0048*
				[3.0]		[1.8]
Volatility, US				0.2589*	Weekend	-0.0306
				[1.8]		[-0.9]
Intercept	-0.0235	-0.125**	-0.030	-0.539***		-0.5834
	[-0.3]	[-2.0]	[-0.8]	[-2.8]		[1.6]
R^2	0.062	0.013	0.031	0.021		0.017
Num. Obs.	3653	3,645	3,654	3,645		3,654

Table 8

EU-open returns on European holidays

This table compares average EU-open returns, volatility, and trading volume on EU holidays with the rest of the sample. We report statistics for EU-open and the rest of the European session ("EU"). Normalized volume and volatility are computed relative to their prior monthly average. EU holidays include days when London or Frankfurt stock exchanges are closed but US stock market is open. The last two columns report the difference between the two samples and its *t*-statistic which is adjusted for autocorrelation and heterogeneity. The last row reports the sample size.

	EU Holidays	Rest of sample	Difference	*t*-stat. for difference	Relative change
Return, EU-Open, %	-0.49	7.78	-8.27	[-2.2]	
Return, EU, %	9.49	-0.37	9.87	[1.5]	
Log volume, EU	12.589	13.474	-0.885	[-10.1]	-6.6%
Log volume, EU Norm.	0.468	1.021	-0.553	[-21.0]	-54.1%
Volatility, EU	2.507	3.477	-0.971	[-9.3]	-27.9%
Volatility, EU, Norm.	0.807	0.992	-0.185	[-11.7]	-18.7%
|Return|, EU	0.410	0.723	-0.312	[-6.8]	-43.2%
Num. Obs.	81	3,574			

Table 9

VIX futures returns during EU-open and other intervals

This table reports main statistics for VIX futures returns including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns (period return times 252). E.g., average return during EU-open is -46.26% annualized. We also report return distribution percentiles, which are not annualized (e.g., minimum return during EU-open is -13.62%). The entire trading day (last column) is split into Asia before EU-open, EU-open, rest of the day until US close ("post-EU-open") and the period around US close. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance.

	Asia pre-EU-open	EU-open	Post-EU-open	U.S.-close	Total
	6:00 pm-11:30 pm	11:30 pm-3:30 am	3:30 am-2:00 pm	2:00 pm-4:15 pm	6:00 pm-6:00 pm
Average return, % p.a.	39.57	-46.26	-21.39	-50.83	-78.49
t-statistic	2.80	-5.20	-0.88	-2.20	-2.13
Standard deviation, %	28.63	18.04	49.53	46.90	74.85
Sharpe ratio, p.a.	1.38	-2.56	-0.43	-1.08	-1.05
Skewness	8.35	-2.07	0.61	7.67	1.73
Kurtosis	154.93	24.69	4.65	150.93	17.74
Min, %	-10.79	-13.62	-10.88	-10.89	-18.91
5%	-1.79	-2.02	-4.65	-3.93	-7.02
25%	-0.40	-0.62	-1.92	-1.39	-2.75
50%	0.00	0.00	-0.38	-0.27	-0.62
75%	0.62	0.36	1.42	0.70	1.59
95%	1.86	1.38	5.67	3.92	7.23
Max, %	35.15	5.14	13.03	58.24	48.07
Max drawdown, %	13.82	87.42	90.71	94.54	98.99

Figure 3
Subperiod returns with confidence intervals

This figure shows how cumulative return varies over a day with corresponding 95%-confidence intervals in grey. The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm to 3:30 am (EU-open), 3:30 am to 2:00 pm (EU and US), 2:00 pm to 6:00 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals expand over time as volatility accumulates.

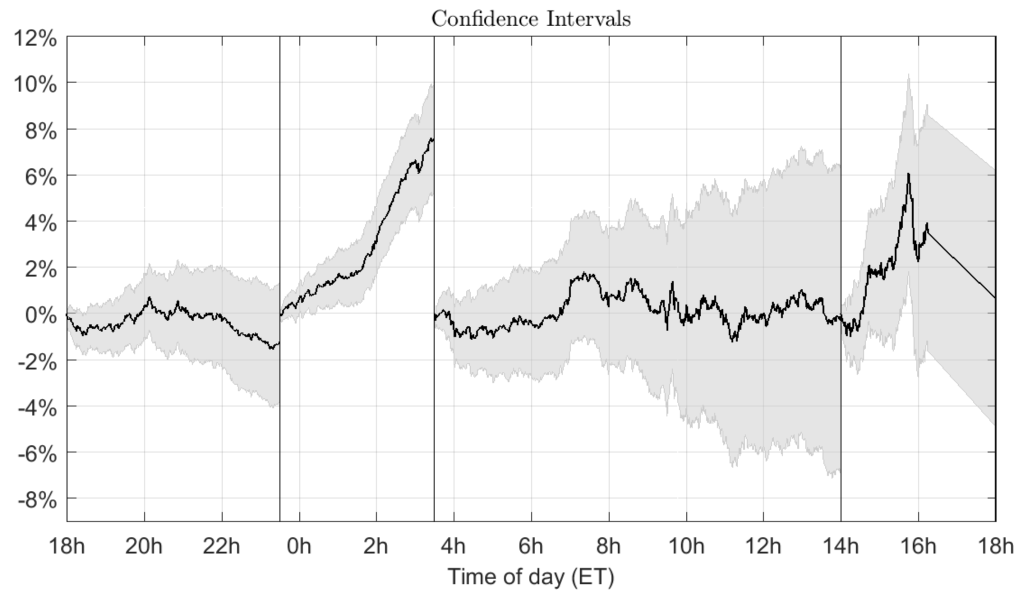


Figure 4
What other intervals have significant returns?
Left (right) panel shows a centered moving average for one-hour (four-hour) cumulative market return during a day. Moving averages are computed at one-minute step. Horizontal dashed lines indicate the 5% and 1% statistical significance levels; *t*-statistic is computed to account for heteroscedasticity and autocorrelation. EU-open period is shaded grey. Market return is computed from E-mini S&P future prices.

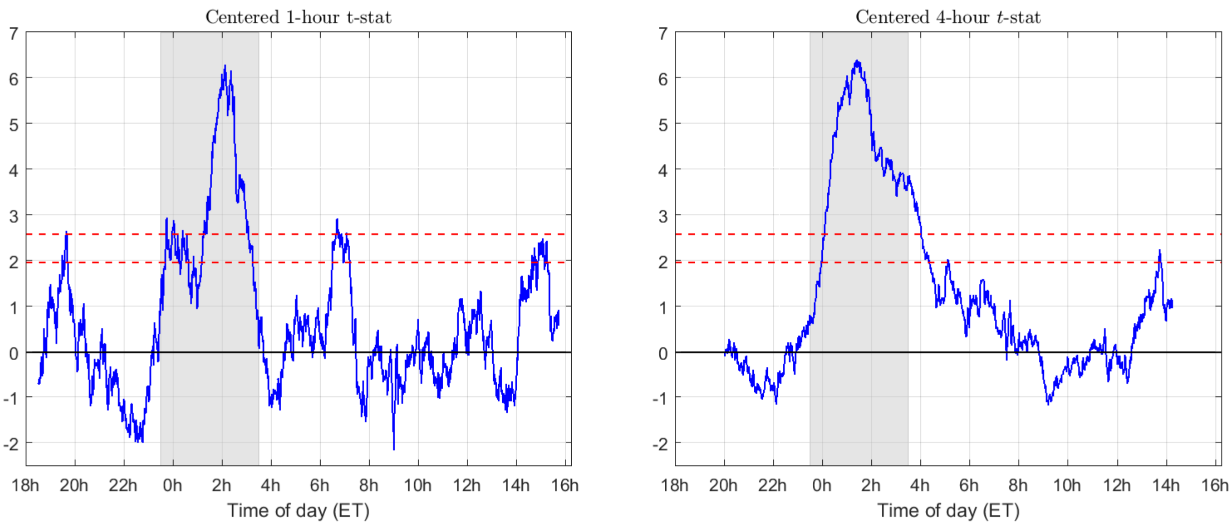


Figure 5
Trading activity and liquidity around the clock

This figure shows how trading activity and liquidity change over a day. Volatility (Panel A) is computed as an annualized standard deviation across one minute realized returns across all days. Trading volume (Panel B) is in future contracts per minute. Volume is shown in log scale as it is extremely skewed. Market depth (Panel C) is an average of sizes at the best bid and ask. The bid-ask spread (Panel D) is in ticks. Average trade size (Panel E) is trading volume in contracts divided by the number of trades. Plots are shown at one-minute frequency. Vertical dashed lines indicate the European and US market open times.

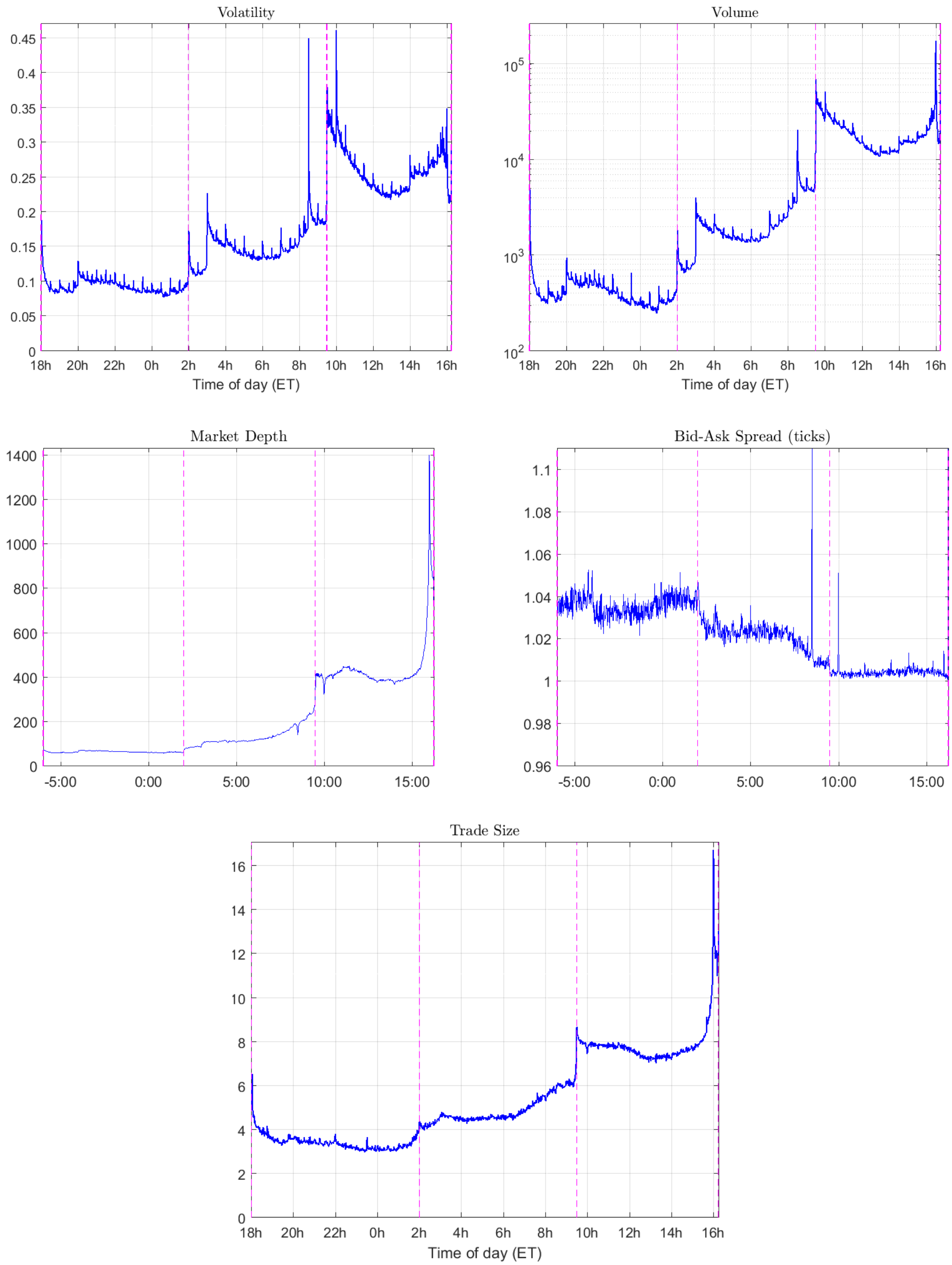


Figure 6

Excess market return and its *t*-statistic over the sample period

Top panel shows a two-year moving average for cumulative market return for EU-open (blue, stable line) period and the rest of the day (RoD, green, volatile line) over the sample period from 2004 to 2018. Vertical dashed lines indicate the 2008 financial crisis (August 1, 2007 to April 1, 2009). Bottom panel repeats the analysis for *t*-statistics of the cumulative market return. Horizontal dashed lines indicate the 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. Market return is computed from E-mini S&P future prices.

Figure 7

US/Europe versus Asia daylight saving time change

This figure shows cumulative market return (left panels) and minute-by-minute trading volume (right panels) around EU-open. Top panel reports results in US time (ET), while bottom panel reports the same results but in Asian time (JST). Asia does not observe daylight savings time (DST), while the US and Europe do. "Summer" is the period when both US and Europe observe DST (i.e., shift one hour ahead compared to the rest of the year ("Winter")). The return and volume patterns remain the same in US time but shift in Asian time. ET is local Eastern Time, equal to Eastern Standard Time (EST) in winter and Eastern Daylight Savings Time (EDT) in summer; JST is Japan Standard Time. Trading volume is the number of contracts per minute. Cumulative return is annualized. Vertical solid lines indicate the EU-open period.

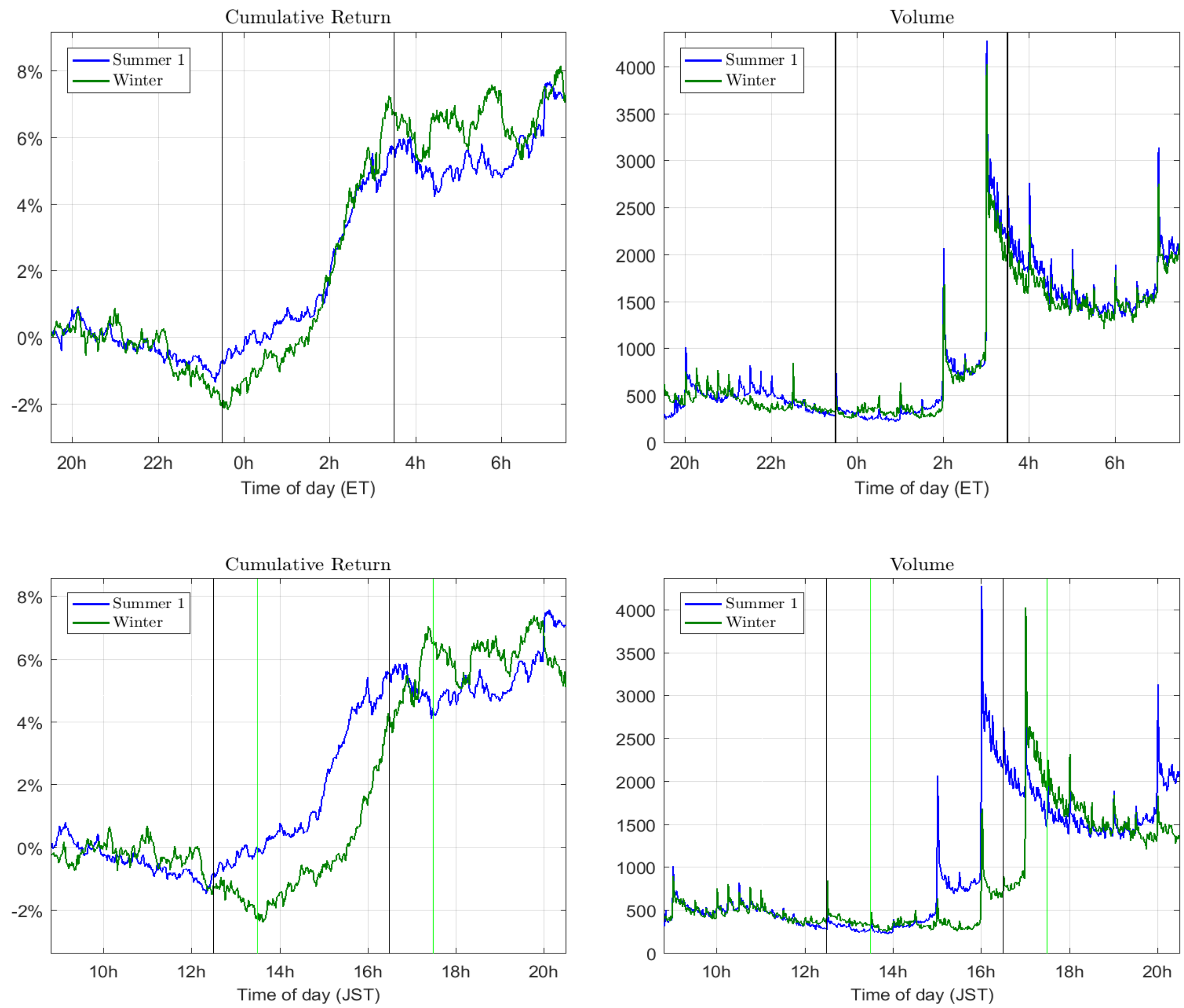


Figure 8
Weekends versus weekdays
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for weekends (Mon, Friday-to-Monday) with regular weekdays (non-Mon). There is little difference between the two. Cumulative return is annualized. Solid vertical dashed lines mark the EU-open period boundaries. Vertical dashed lines separate the three trading sessions.

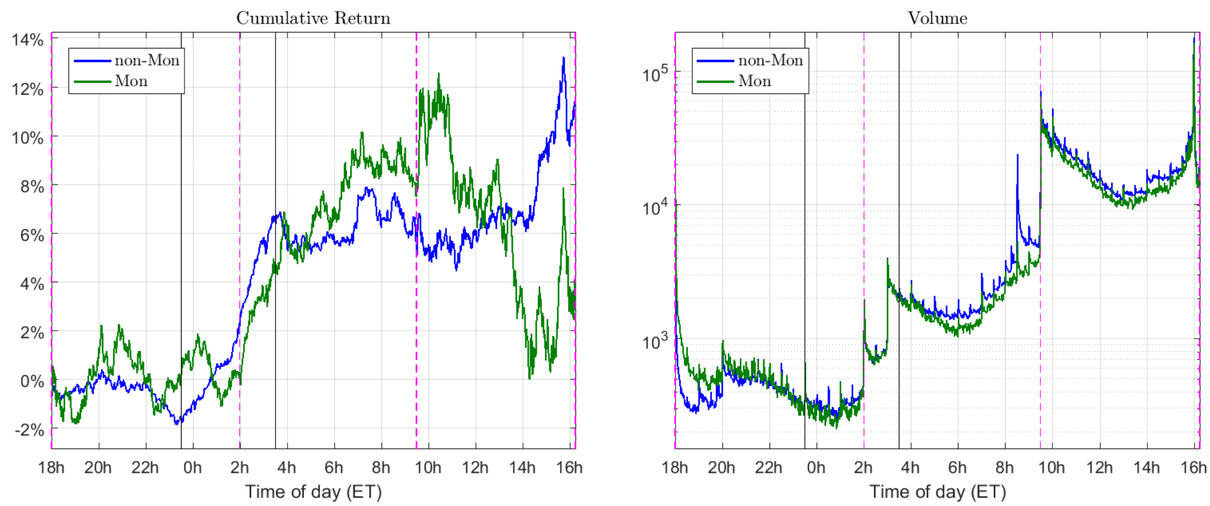


Figure 9
First and second part of the sample
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for the first (pre-2011) and second (post-2011) part of the sample period. Trading volume increased markedly during post-2011, but the EU-open return pattern remained unchanged. Cumulative return is annualized. Solid vertical dashed lines mark the EU-open period boundaries. Vertical dashed lines correspond to the European and US market open times.

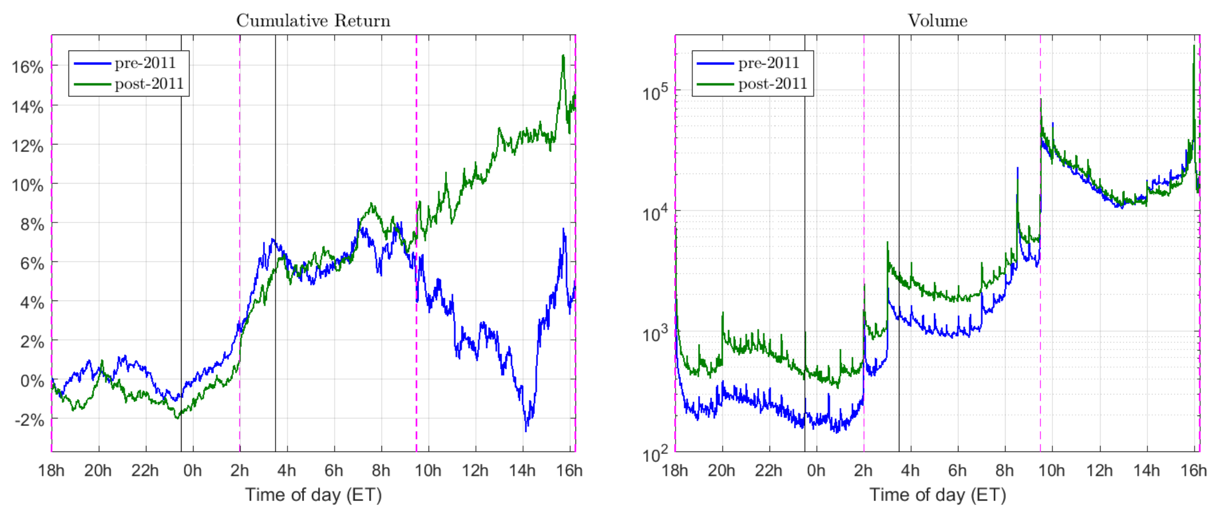


Figure 10
Variance ratio for daily returns

This figure shows how return variance depends on time of the day when prices are taken to compute 24h returns and then their variance. Variance at time *t* is computed as average over all days of squared returns from *t* to *t+24h*. We then report a ratio of variance at time *t* to overall daily average variance (over all starting times). For example, 1.08 at 0:00h means that variance is 8% higher than average for the 18:00-to-18:00 returns. Variance ratio is often used as measure of how noisy prices are.

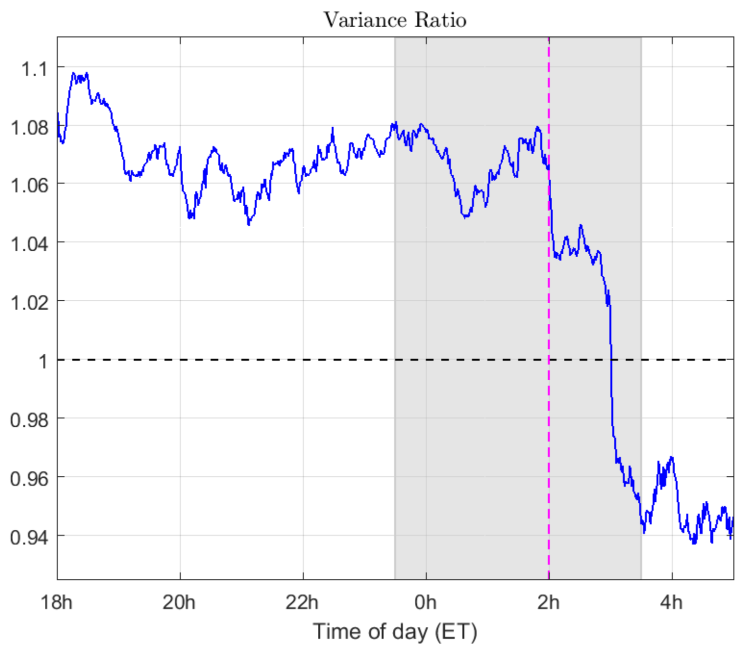


Figure 11

VIX futures returns with confidence intervals

Top panel shows how cumulative return for VIX futures varies over a day with corresponding 95%-confidence intervals (in grey). The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm until 3:30 am (EU-Open), 3:30 am to 2:00 pm (EU and the US), 2:00 pm to 4:15 pm (US-close). Cumulative return is reset to zero at the start of each interval. Confidence intervals expand over time as volatility accumulates. Extended hours for VIX futures start spanning EU-open on July 2014, and the sample ends in July 2018. Bottom panels show a centered moving average for one-hour (four-hour) cumulative VIX future return during a day. Horizontal dashed lines indicate 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. EU-open period is shaded grey. Plots are shown at 5-minute frequency.

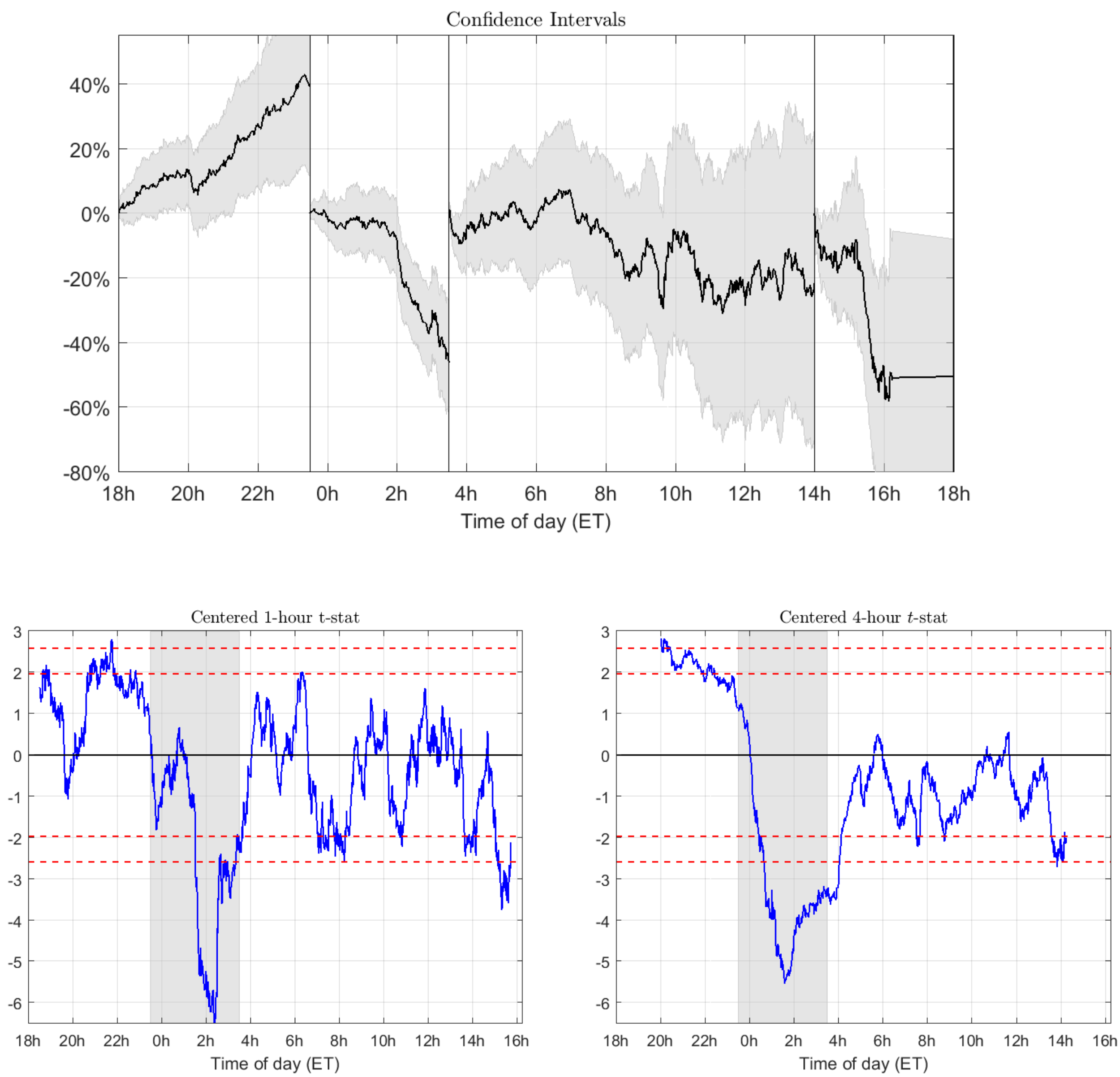
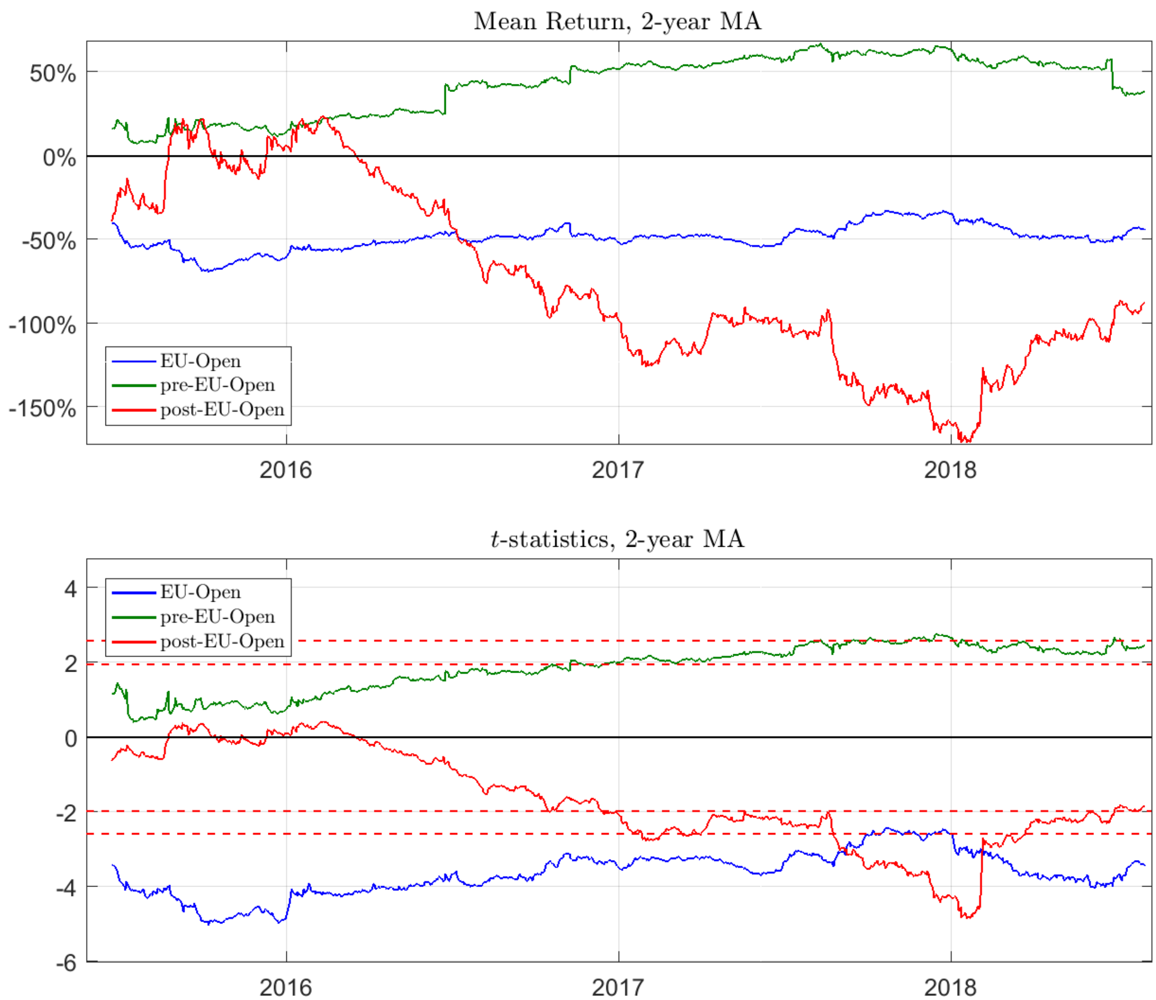


Figure 12

Excess VIX futures return and its *t*-statistic over the sample period

Top panel shows a two-year moving average for cumulative VIX future return for overnight session prior to EU-open (green line, around +50%), EU-open (blue line, around -50%), and post-EU-open (rest of the day, red volatile line) periods over the sample period from July 2014 to July 2018. Bottom panel repeats the analysis for *t*-statistic of the cumulative VIX future return. Horizontal dashed lines indicate the 5% and 1% statistical significance levels. *t*-statistic is computed to account for heteroscedasticity and autocorrelation. Log return is computed from front-month VIX future prices.



Appendix

This appendix describes how volatility, volume, and liquidity change over a day and presents additional figures and tables.

A.1 Volume, volatility, and liquidity around the clock

We focus on average market return, but other market variables such as volatility, volume, the bid-ask spread, and market depth also show interesting patterns around the clock. Figure 5 shows how these four variables change over a day at a one-minute resolution. As expected, volatility and volume generally follow each other, but volume changes are much more dramatic. Therefore, it is shown on a log scale. Several episodes stand out. First, US macro announcements correspond to the two biggest (one-minute) volatility spikes at 8:30 am and 10:00 am; however, the spikes quickly revert to a normal volatility level. Volume spikes are less pronounced. Perhaps macro news affects prices but does not trigger large portfolio rebalancing. Market depth decreases while the bid-ask spread increases as liquidity providers avoid announcement uncertainty. Even though these two minutes that contain US macro news have high volume and volatility, average returns are not significantly different from zero during these periods.

Second, volatility and volume are U-shaped during the US session and pre-US European session. For the pre-US European session, volume is much higher approaching US open as US investors arrive to the market. For the US session, volume is the highest at 4:00 pm then drops during the last 15 minutes. The Asian session's pattern differs. Volatility and volume spike at Hong Kong/China open and then gradually decrease until European open. The European session has its first spike when Frankfurt opens. Then, volume quickly reverts to the Asian level. However, a much bigger spike occurs during London open, which makes volatility and volume permanently higher than in pre-period. Third, volatility and volume spike at 6:00 pm when GLOBEX re-opens after a technical break and investors trade on the information accumulated during the break. Finally, both measures have small spikes at every round-numbered half-hour due to investor preference for round numbers. Andersen, Bondarenko, Kyle, Obizhaeva (2018) use intraday trading invariance hypothesis to explain relationship between volume, volatility, and trade size in the E-mini S&P 500 futures market.

Importantly, one of the biggest spikes in trading volume during the Asian session occurs exactly at 11:30 pm, right at the start of the EU-open period. This spike is comparable to the one occurring during Hong Kong/China open. Like the Hong Kong/China open volatility spike, the volume quickly reverts to normal. The corresponding volatility spike is much smaller and is comparable to other round-hour spikes. During EU-open, the two major spikes occur during European and London open. Volatility reverts to Asian levels quickly after the spike at European open, but volume remains high. On the other hand, London open permanently elevates volatility and volume after the initial spike.

Market depth and bid-ask spread are obviously related to volatility and volume but also have individual patterns. Market depth increases exponentially in the period approaching US close, reaching levels that are three times higher than during the rest of the US session. The bid-ask spread is almost always one tick. It drops during China/Hong Kong open, increases slightly during EU-open, but decreases after Europe opens. The spread has two large spikes during US macro announcements.

Table A.1
Excess market returns for intraday intervals
This table reports essential statistics for E-mini S&P future returns including average return, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. All these measures are computed from annualized log returns and, when applicable, are reported as percent. We also report return distribution percentiles, which are not annualized. Intraday intervals include the overnight session before EU-open, first and second halves of EU-open, Asian, European, and US sessions, the period between US close (4:15 pm) and E-mini re-open (6:00pm), and finally the entire day in the last column. Max drawdown is the difference between a portfolio's point of maximum return and any subsequent low point of performance.

	Asia pre-EU-open	EU-open 1st Half	EU-open 2nd Half	Asia	Europe	US	Post US-close	Total
	6:00 pm-11:30 pm	11:30 pm-1:30 am	1:30 am-3:30 am	6:00 pm-2:00 am	2:00 am-9:30 am	9:30 am-4:15 pm	4:15 pm-6:00 pm	6:00 pm-6:00 pm
Average return, % p.a.	-1.25	1.70	5.90	1.80	4.39	3.44	-2.83	6.80
t-statistic	-0.95	2.51	5.85	1.21	2.16	0.89	-2.89	1.39
Standard deviation, %	5.01	2.57	3.84	5.67	7.73	14.75	3.73	18.63
Sharpe ratio, p.a.	-0.25	0.66	1.54	0.32	0.57	0.23	-0.76	0.36
Skewness	-2.14	-0.23	1.46	-1.37	-0.13	-0.50	-1.68	-0.42
Kurtosis	37.56	36.22	42.00	35.02	11.33	15.27	84.37	16.80
Min, %	-4.06	-2.11	-2.58	-5.41	-3.23	-9.15	-4.61	-12.01
5%	-0.41	-0.18	-0.28	-0.47	-0.71	-1.43	-0.24	-1.73
25%	-0.10	-0.04	-0.07	-0.11	-0.18	-0.35	-0.06	-0.39
50%	0.00	0.00	0.02	0.00	0.02	0.06	0.00	0.08
75%	0.11	0.05	0.11	0.13	0.23	0.43	0.04	0.54
95%	0.37	0.20	0.35	0.45	0.71	1.26	0.22	1.57
Max, %	2.94	1.87	3.81	3.11	3.70	7.53	3.69	11.28
Max drawdown, %	25.35	3.37	8.44	10.35	30.28	44.55	0.00	61.89

Table A.2
Trading activity over time
The table shows trading activity for E-mini S&P futures during Asian, European, and US sessions by year. Note how Asian share of trades jumps from 0.07% in 2002 to 1.28% in 2004. The last three columns sum up to 100%.

	Total number of trades				Percentage of total		
	Asia	Europe	U.S.	Total	Asia	Europe	US
1998	0.08	3.01	44.78	47.87	0.18	6.29	93.53
1999	0.08	4.77	93.51	98.37	0.08	4.85	95.07
2000	0.08	5.87	147.74	153.69	0.05	3.82	96.13
2001	0.14	10.06	220.87	231.07	0.06	4.35	95.58
2002	0.26	16.90	362.32	379.49	0.07	4.45	95.48
2003	2.53	25.04	400.09	427.67	0.59	5.86	93.55
2004	7.40	38.47	532.50	578.37	1.28	6.65	92.07
2005	7.03	42.80	562.73	612.56	1.15	6.99	91.86
2006	5.32	33.24	313.24	351.79	1.51	9.45	89.04
2007	13.60	81.73	597.10	692.43	1.96	11.80	86.23
2008	40.43	213.13	1320.61	1574.16	2.57	13.54	83.89
2009	45.06	231.63	1329.34	1606.03	2.81	14.42	82.77
2010	78.13	459.68	2208.24	2746.05	2.85	16.74	80.42
2011	114.85	577.09	2474.45	3166.39	3.63	18.23	78.15
2012	92.50	469.62	1905.24	2467.36	3.75	19.03	77.22
2013	84.88	363.54	1957.63	2406.05	3.53	15.11	81.36
2014	79.38	394.30	2090.03	2563.70	3.10	15.38	81.52
2015	72.59	239.15	1212.90	1524.64	4.76	15.69	79.55
2016	90.11	209.65	889.17	1188.93	7.58	17.63	74.79
2017	46.87	107.82	559.94	714.63	6.56	15.09	78.35
2018	106.59	203.65	1128.66	1438.90	7.41	14.15	78.44

Table A.3
Market return for the extended sample by year

This table reports several statistics for E-mini S&P futures returns by year. While the main analysis is based on the sample from 2004 to July 2018, this table extends the sample to 1998. However, prior to 2004 the Asian session was very illiquid (see Table A.2). Furthermore, prior to July 2003 E-mini S&P only traded starting from 1:00 am. That is, the Asian session was open for only 1 hour instead usual 8 hours and EU-open was open for 2.5 hours instead of 4 hours. After July 2003, 2:00 am the trading hours were extended to the current 6:00 pm or nearly 24 hours. The statistics include average return, *t*-statistics, standard deviation, and Sharpe ratio. All these statistics are based on annualized log returns (period return times 252) and, when applicable, are reported as percent. The entire trading day is split into EU-open (from 11:30 pm to 3:30 am) and the rest of the day (6:00 pm to 11:30 pm and 3:30 am to 6:00 pm). *t*-statistic is computed to account for heteroskedasticity and autocorrelation. Last two rows report averages for two subsamples.

	EU-open				Rest of the day			
	Exp. return	Std. dev.	Sharpe ratio	*t*-statistic	Exp. return	Std. dev.	Sharpe ratio	*t*-statistic
1998	3.11	3.31	0.94	0.94	17.33	21.43	0.81	0.81
1999	4.64	2.09	2.22	2.22	9.02	18.67	0.48	0.48
2000	11.76	2.22	5.29	5.29	-28.39	22.80	-1.25	-1.25
2001	-1.52	3.34	-0.46	-0.45	-16.48	20.58	-0.80	-0.79
2002	0.73	4.05	0.18	0.18	-27.73	26.26	-1.06	-1.06
2003	3.25	3.25	1.00	1.00	20.17	16.90	1.19	1.19
Average:								
1998-2003	3.66	3.04	1.53	1.53	-4.35	21.11	-0.10	-0.10
2004-2018	7.65	3.96	2.19	2.15	-0.82	15.81	0.25	0.26

Table A.4
EU-open first half versus second half

We split EU-open into two two-hour periods: from 11:30 pm to 1:30 am ET (1st half) and from 1:30 am to 3:30 am ET (2nd half). The table reports average annualized return, standard deviation, contract trading volume, and trade size for E-mini S&P 500 futures and VIX futures. The statistics are computed over the period from January 2004 to July 2018 for E-mini S&P 500 futures and over the period from July 2014 to July 2018 for VIX futures. We also report the difference between the two periods and *t*-statistic for the difference, which is computed to account for heteroskedasticity and autocorrelation.

	EU-Open			
	1st half	2nd half	Diff.	*t*-stat.
E-mini S&P return	1.70	5.90	4.21	3.92
E-mini S&P volatility	0.11	0.15	0.04	23.93
E-mini S&P volume, 000s	37.74	132.17	94.43	20.57
E-mini S&P trade size	3.21	4.27	1.05	16.48
VIX return	-4.56	-41.70	-37.14	-3.55
VIX volatility	0.40	0.66	0.26	21.01
VIX volume, 000s	1.84	5.22	3.38	13.58
VIX trade size	3.85	4.80	0.95	5.64

Figure A.1
Returns in calendar and variance time

This figure shows cumulative market return over a trading day in regular calendar (left) and variance (right) clocks. In variance clock, the time slows down or speeds up so that the rate of the accumulated return variance is constant. That is, the cumulative return trajectory does not change but the horizontal axis is deformed to reflect varying speed of stochastic clock. Market return is computed from E-mini S&P future prices. Cumulative return is annualized by multiplying period return by 252. Vertical dashed lines indicate the European and US open times; grey area indicates the EU-open period.

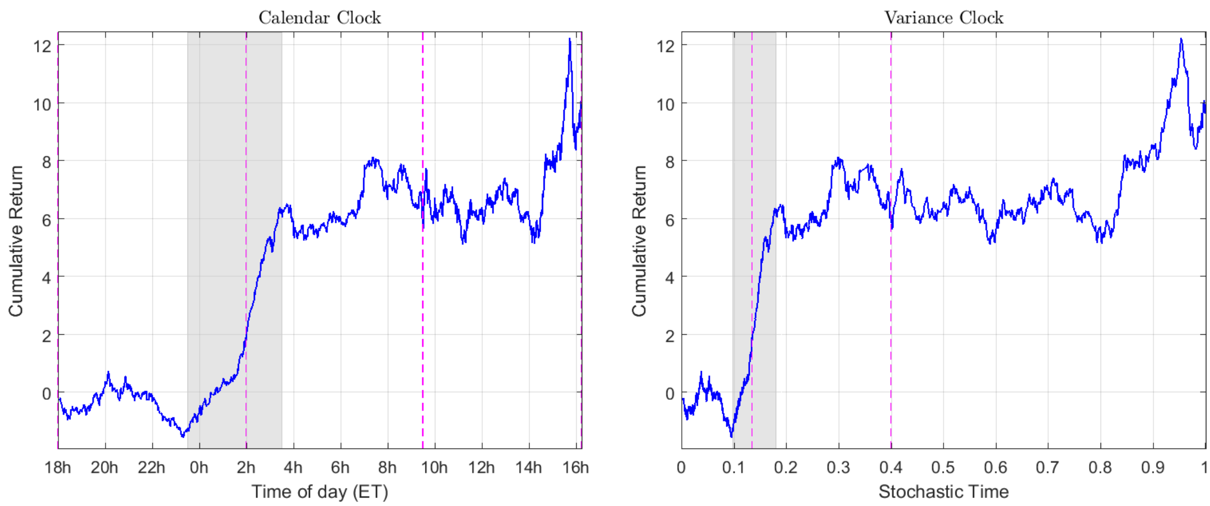


Figure A.2
Cumulative market return over time

Top panel shows cumulative market return for EU-open (blue, stable line) period and the rest of the day (RoD, green, volatile line) from 2004 to 2018. Vertical dashed lines indicate the 2008 financial crisis (August 01, 2007 to April 01, 2009). Bottom panel shows contribution of EU-open to the total daily return variance. This contribution is computed as a ratio of the realized variance for EU-open to the realized daily variance. Thick red line shows a two-year moving average. Market return is computed from E-mini S&P future prices.

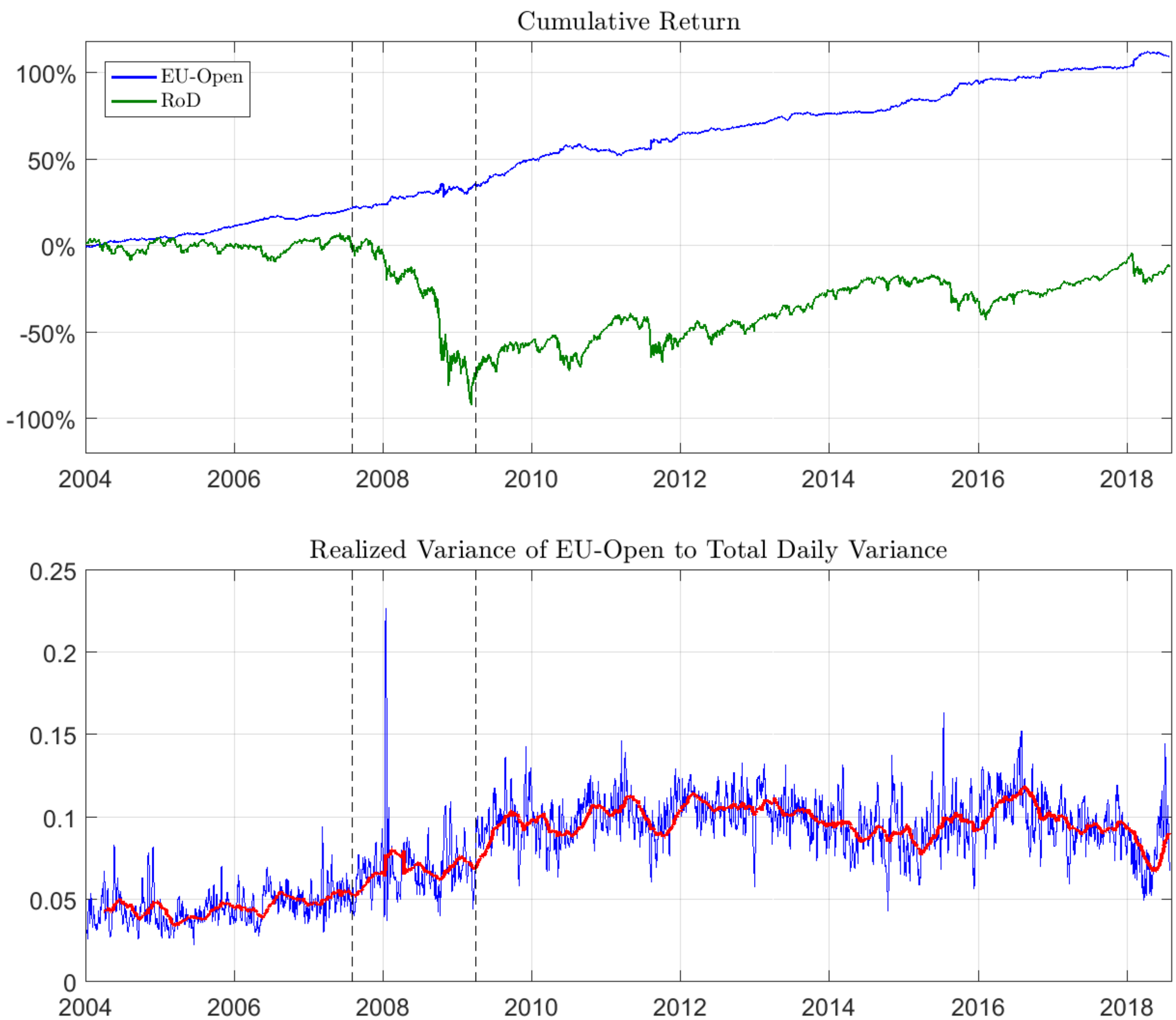


Figure A.3
Cumulative returns for baseline and conditional strategies over time
The strategy buys E-mini future at the start of EU-open and closes position at the end of EU-open. Top and bottom panels show cumulative returns before and after transaction costs, respectively. Conditional strategy trade only on 40% of days with high expected EU-open return. Each trade involves the same capital. Transaction costs include the bid-ask spread and the round-trip exchange fees and commissions. Vertical dashed lines mark the 2008 financial crisis.

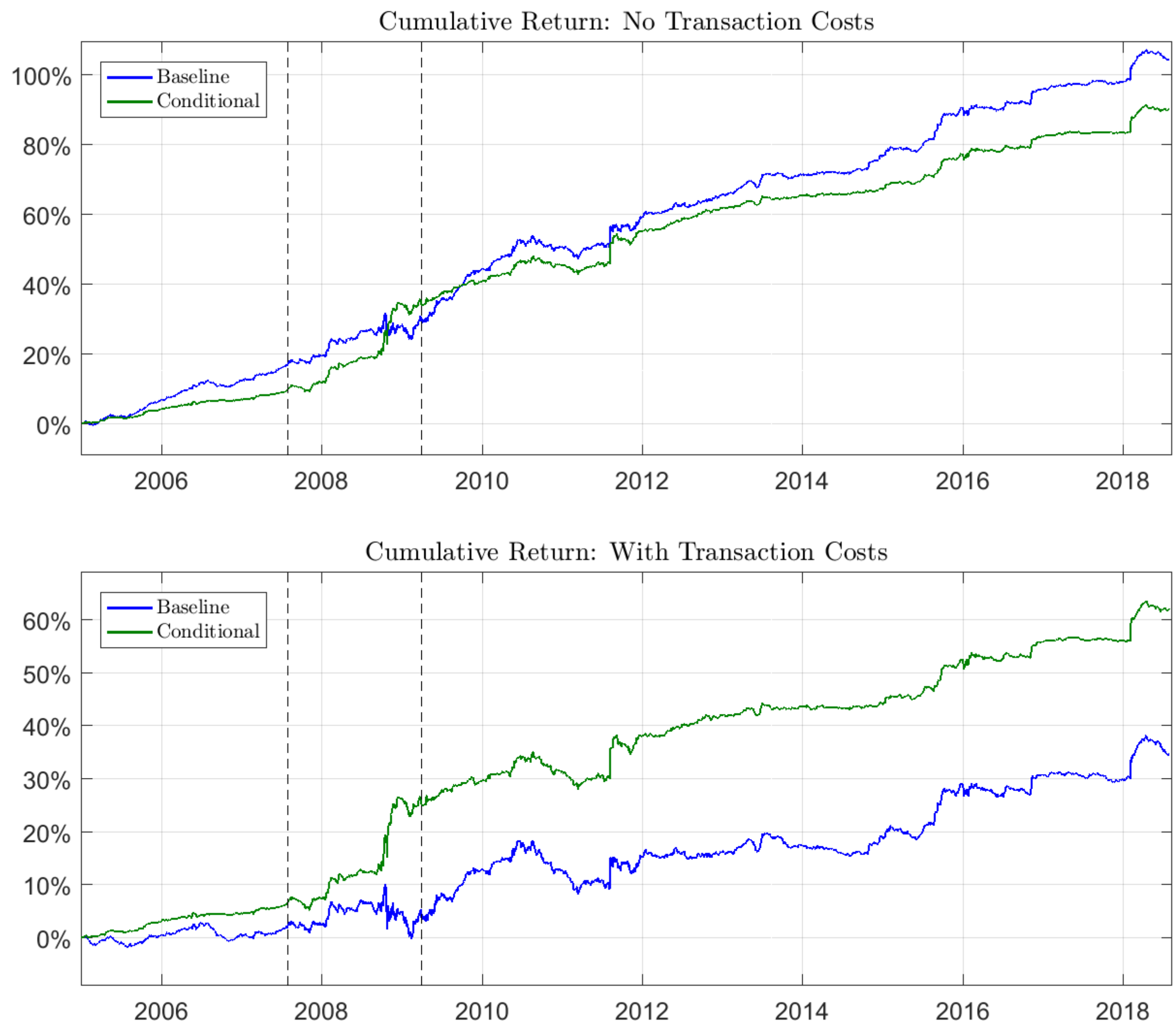


Figure A.4
Conditional trading strategy
The figure shows the R^2 of the predictive model (left panel) and fraction of days when the conditional strategy trades (right panel). The model use as predictors daily change in VIX and Asian volatility. We report three types of R^2. The blue, time-varying line shows (in-sample) R_t^2 of the predictive model estimated in month t, with expanding estimation window. The two horizontal dashed lines indicate the in-sample and out-of-sample R_{OS}^2 estimated for the full sample: R_{IS}^2 (black) and R_{OS}^2 (red). The out-of-sample R_{OS}^2 is computed following the approach in Campbell and Thompson (2008). The conditional strategy trades on about 40% of days (indicated with the dashed line on the right panel) for which the model predicts higher expected EU-return. The fraction of days selected is shown as a 3-month moving average.

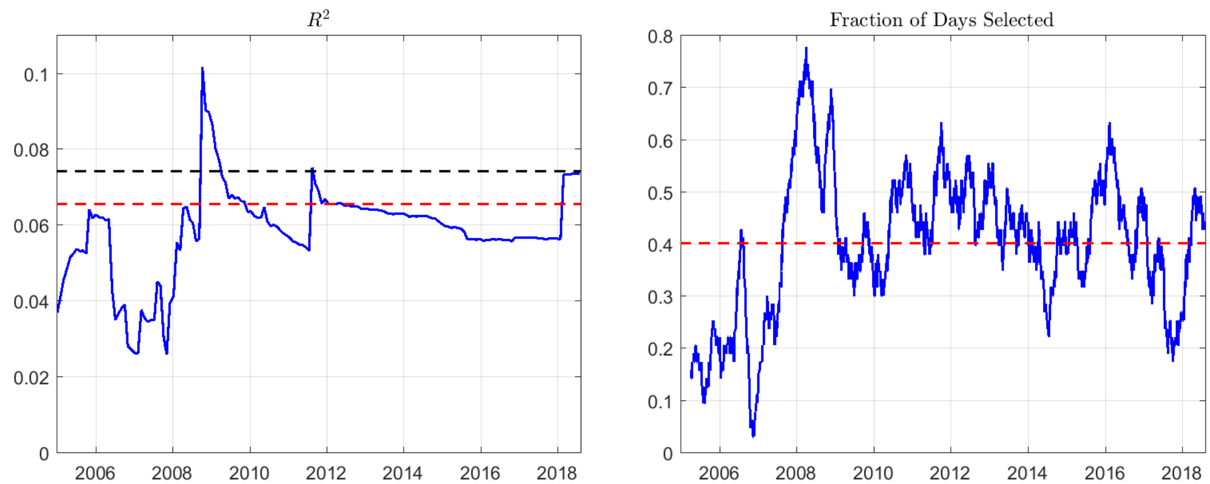


Figure A.5

Cumulative returns for VIX futures over the sample period

Top panel shows a two-year moving average for cumulative VIX futures return during the Asian session before EU-open (green, increasing line), EU-open (blue, decreasing line) and the rest of the day post EU-open (red, volatile line) over the sample period from July 2014 to July 2018.