Market Return Around the Clock: A Puzzle☆

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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 actively traded for almost 24 hours. Strikingly, four hours around European open account for the entire average market return. This period's returns are positive every year and have a 1.6 Sharpe ratio that remains high after costs. Average returns are a noisy zero during the remaining 20 hours. High returns around European open are consistent with European investors processing information accumulated overnight and thus resolving uncertainty. Indeed, uncertainty reflected by VIX futures prices rises overnight and falls around European open. The results are stronger during the 2020 COVID crisis.

JEL Classification: G12, G13, G14

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

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We study how the excess market return depends on the time of the day using E-mini S&P 500 futures actively traded for almost 24 hours. Strikingly, four hours around European open account for the entire average market return. This period's returns are positive every year and have a 1.6 Sharpe ratio that remains high after costs. Average returns are a noisy zero during the remaining 20 hours. High returns around European open are consistent with European investors processing information accumulated overnight and thus resolving uncertainty. Indeed, uncertainty reflected by VIX futures prices rises overnight and falls around European open. The results are stronger during the 2020 COVID crisis.

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"Information is the resolution of uncertainty."
Claude Shannon

1. Introduction

When are market returns positive? We study how the excess market return reflected by the S&P 500 index changes over day and night. E-mini S&P 500 futures are actively traded at night, and their returns equal the excess returns on the S&P 500 index.[1] Figure 1 shows how average cumulative returns of E-mini futures depend on the time of day spanning 24 hours. Average returns during one period stand out. After flat (zero) returns during the beginning of the night, the cumulative returns rapidly increase between 11:30 pm and 3:30 am and become flat again afterward. These four hours, which we call "EU-open," produce a 7.6% annualized return and correspond to deep night in America. European stock markets open, and Asian markets close during this time. In contrast, total returns for the rest of the day are -0.8% p.a. and are flat for the entire day except for a zig-zag around US close – during this extremely volatile period, returns rapidly increase and revert with a small net effect. Our main goal is to explore why returns are high during EU-open and low during the rest of the night, but we also study the zig-zag.

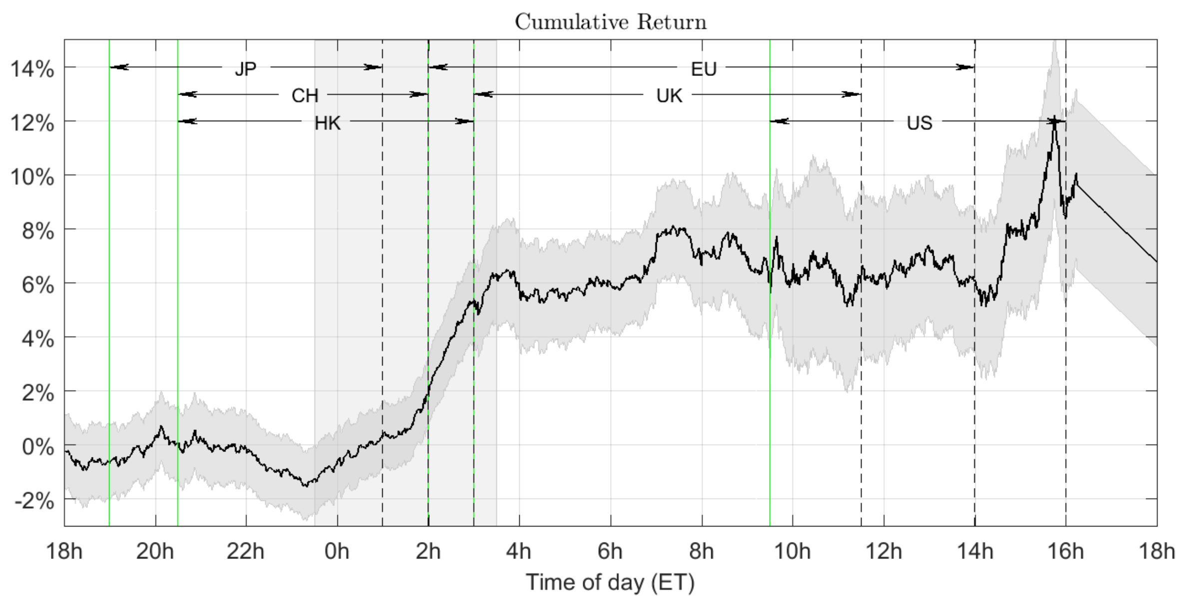

Figure 1. Annualized (average cumulative log) returns for S&P 500 E-mini futures as a function of time of the day in Eastern Time (ET). The band around returns reflects two standard deviations for returns over a prior hour. Line arrows denote open and close times for major stock markets. The straight line from 4:15 to 6:00 pm denotes a single return as the market is only open for 30-minutes. The EU-open period is in grey. Annualized return equals the period return times 252. The sample period is from January 2004 to July 2018.

[1] S&P 500 E-mini futures are commonly used to measure the excess market return. They are already net of the risk-free rate and include dividends. Kawaller, Koch, and Koch (1987) and Hasbrouck (2003) shows that S&P futures lead the spot index and account for most price discovery.

It is known that the close-to-open period generates most of the daily stock returns.[2] Any theory of market return must explain this puzzle. Yet, none of them do: "We can show that the (day-night return) gap exists, but at this point, we don't know exactly why" (New York Times, 2/2/2018). This paper helps to resolve the puzzle. First, we bring new data – high-frequency returns from the overnight period – and show that the returns are positive *only* from 11:30 pm to 3:30 am. Second, existing theories struggle to explain this return pattern. But the uncertainty resolution hypothesis is largely consistent with it.[3] Relatively small spikes in information uncertainty at night can produce a return premium that adds up to the total annual market return.

EU-open returns are highly consistent and robust; a 7.6% annualized return has a Sharpe ratio of 1.67 and a *t*-statistic of 6.4. Returns are positive every year. A skeptical reader can pick and drop any ten calendar years, and yet EU-open return remains significant in the remaining 4.5 "worst" years. Data snooping tests, including the Bonferroni procedure and the reality check of White (2000), confirm that EU-open results are not due to picking the best performing period of the day. These tests also alleviate a related concern that expected returns are computed as an average of realized returns and can depend on a sample period. In contrast, cumulative return during the rest of the day is not statistically significant in almost all its sub-intervals.

Can overnight illiquidity explain EU-open returns? Most futures are illiquid outside of regular trading hours. But the S&P 500 E-mini is by far the most liquid index product during the day and remains among top-5 most actively traded index futures during Asian hours. Investors can trade in size and at low cost at night; $14 billion of S&P exposure is traded during a typical EU-open with two hundred trades per minute and a 0.017% bid-ask spread. Also, EU-open appears less risky than the rest of the day by simple risk measures. Volatility is lower, and returns are positively skewed, which many investors prefer, while daily return skewness is negative.

We test our original results out-of-sample on data from 2020, a year of unprecedented uncertainty due to COVID. Positive market returns are still concentrated precisely during EU-open with a 24% return, three times higher than in the main sample. EU-open returns are particularly high between mid-February and April when the stock market first crashed and then rallied. The 2020 results validate the EU-open period and support the uncertainty resolution hypothesis.

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[2] Cliff, Cooper, and Gulen (2008), Kelly and Clark (2011), Berkman, Koch, Tuttle, and Zhang (2012) among others.
[3] It also relates to a broad literature on uncertainty – Epstein and Zin (1989), Dixit and Pindyck (1994), Bloom (2009), Pastor and Veronesi (2012).

After documenting the EU-open puzzle, we try to explain it. First, the open of European stock markets and not the close of Asian markets causes the EU-open price run-up. Asian close and European open are the main recurrent events during the four hours. The change in daylight saving time serves as an exogenous shock that helps us distinguish between Asia's and Europe's impacts. Since Asia does not observe daylight saving time, Asian time shifts by an hour relative to Europe for half a year. The price run-up during EU-open does not change in European time but shifts in Asian time. Thus, Europe causes the price run-up – hence the name "EU open".

We consider a broad range of potential explanations, of which uncertainty resolution is most consistent with the data. Information uncertainty arises because price deviates from unobserved fundamental value. Quoting Black (1986): "All estimates of value are noisy, so we can never know how far away price is from value." High information uncertainty makes an asset riskier causing a price discount. Several theories clarify why asset prices increase as information uncertainty is resolved (e.g., Hong and Wang, 2000; Hu, Pan, Wang, and Zhu, 2019). These theories focus on how information flows over time, while we highlight another market friction – periodic drops in the market's capacity to process information.

The uncertainty resolution hypothesis implies that market returns should be low through the night pre-EU-open, when uncertainty accumulates, and high during EU-open, when uncertainty is being resolved, which matches the return dynamics in Figure 1. Returns inversely follow changes in uncertainty. Uncertainty accumulates overnight because a critical mass of investors is needed to fully process arriving information, which is much broader than just broadcasted news. Although Asian investors respond to information, it gets fully impounded into prices only when Europeans arrive, leaving little for Americans to add. The Asian economy is a powerhouse that impacts the S&P 500, but its asset management industry is relatively small and does not specialize in quantifying the effect of local news on global stocks.[4] E-mini price increases gradually during EU-open on average as investors arrive at different times: some wake up early, most join during its second part when Frankfurt or London exchanges open.

Several independent tests support this hypothesis. *First*, many European investors skip trading on unique EU holidays, a quasi-exogenous shock to the number of investors who resolve

[4] The International Monetary Fund reports that in 2019 Asia contributed $31.6T toward the world's GDP, more than Europe ($21.8T) and North America ($24.4T). However, few large investors operate in this time zone: the 2017 survey shows that AUM in Asia is $4.58T, or 2.8 and 6.7 times lower than in Europe and the US, respectively.

uncertainty during EU-open. Consistent with uncertainty not being resolved, EU-open volume and volatility decrease and returns are slightly *negative* on EU holidays. Positive returns shift to later in the day when US investors arrive and resolve uncertainty. *Second*, VIX futures track uncertainty around the clock. Cumulative returns for VIX futures increase at night before EU-open – the only interval when uncertainty increases. But the positive VIX trend reverses at the start of EU-open, and returns are highly negative during EU-open. *Third*, does higher uncertainty predict higher EU-open returns? EU-open returns are higher if more information arrives overnight as measured by high volatility or volume pre-EU-open. *Fourth*, EU-open returns are also higher after uncertainty increases as measured by VIX index, VSTOXX implied volatility, the news-based economic uncertainty of Baker, Bloom, and Davis (2016), and Twitter-based economic and market uncertainty of Baker, Bloom, Davis, and Renault (2020). *Also*, EU-open returns are three times higher in 2020 – a year of unprecedented uncertainty. *Finally*, prices become 14% more informationally efficient during EU-open according to the variance ratio test.

The return patterns are not an artifact of illiquidity or limits to arbitrage. Consider a simple trading strategy that buys futures right before EU-open and closes the position after its end. Despite trading twice a day, the strategy remains profitable net of conservative estimates of trading costs – exchange fees, commissions, and the bid-ask spread – and its Sharpe ratio exceeds that of the buy-and-hold alternative. This naïve strategy can be greatly improved by only trading when EU-open returns are expected to be higher than average. The conditional strategy predicts EU-open returns out-of-sample with two variables motivated by uncertainty resolution: overnight volatility and daily change in VIX. Profitability more than doubles while costs remain the same, leading to a 1.2 Sharpe ratio. A 6.6% out-of-sample R^2_{OS} is two times higher than for comparable models (e.g., Gao, Han, Li, and Zhou, 2018). These strategies have an approximate capacity of \$9 billion with average after-cost annual profits of \$50 million. Finally, the EU-open anomaly can benefit long-term investors, who can reduce trading costs by buying before (or selling after) EU-open.

Alternative explanations receive little support. Higher night returns can compensate liquidity providers for the risk of holding inventory overnight. According to this hypothesis, market returns should be high during every night hour, but the return is zero between US close and EU-open. Perhaps close-to-open returns are positive because most news arrives at night. US earnings and much macro news are released shortly after the close or right before the open. But EU-open is hours away from these news intensive periods. Perhaps European investors are optimistic and buy at the open. But EU-open returns do not depend on investor sentiment. Higher market return can compensate investors for interest and margin payments incurred overnight. Carry costs are higher over weekends, but weekend EU-open returns are slightly lower. Lastly, EU-open could be a market inefficiency. While we cannot completely rule out this explanation, EU-open performed strongly in 2020, after our results became widely known among practitioners.

Uncertainty resolution can explain why market returns are low at night and high during EU-open. But its implications for average returns during the day are less clear. While average returns are close to zero during US hours, high volatility prevents reliable inference. It remains a puzzle why average returns are low despite high volatility during the day. Finally, we define EU-open to cover the entire positive return period, and the main results hold for alternative definitions. But we do not directly observe when Europeans start trading E-mini in the morning.

This paper contributes to several literatures. Cliff, Cooper, and Gulen (2008) show that the close-to-open period generates most of the daily return for US stocks, settling a debate in earlier studies (Rogalski, 1984; Wood, McInish, and Ord, 1985; Harris, 1986; Smirlock and Starks, 1986). Cliff et al. (2008) suggest that "the effect is driven in part by high opening prices which subsequently decline." Berkman, Koch, Tuttle, and Zhang (2012) argue that large price changes trigger retail investors' attention, who drive up the opening price the next day. These studies do not observe prices at night. In contrast, we show that overnight return is positive *only* during EU-open and relate it to uncertainty resolution. Recently, Boyarchenko, Larsen, and Whelan (2021) argue that inventory risk can explain returns during one hour before the London open because the return is part of a return reversal between US close and London open. Unlike EU-open, this one-hour period misses most of the average return. They primarily focus on return *reversal*, while we focus on *average* return and reject inventory risk hypothesis in favor of uncertainty resolution.

Aboody, Even-Tov, Lehavy, and Trueman (2018), Akbas, Boehmer, Jiang, and Koch (2021), Berkman et. al (2012), Branch and Ma (2012), Bogousslavsky (2021), Hendershott, Livdan and Rosch (2020), and Lou, Polk, and Skouras (2019) argue that different groups of traders tend to dominate the overnight versus daytime trading periods, and their interaction results in the predictable return patterns during the daytime versus overnight. We complement these studies of clientele effects by showing that European investors, who are often neglected, help resolve uncertainty and affect EU-open returns. We also provide stylized facts about average returns that challenge theories of market closures (Slezak, 1994; Longstaff, 1995; Admati and Pfleiderer, 1989;

Foster and Viswanathan, 1990; Hong and Wang, 2000). Information is not processed seamlessly, and the processing capacity drops at night. Finally, average market returns are also concentrated during the pre-FOMC drift (Lucca and Moench, 2015). EU-open makes a 7.6% return p.a. versus 2.9% p.a. for the pre-FOMC drift in our sample – less per event, but more in aggregate.[5]

The paper is organized as follows. Section 2 describes the data and methodology. Section 3 explores overnight liquidity. Section 4 studies how market returns depend on the time of day. Section 5 discusses and tests potential explanations. Section 6 explores the zig-zag around the US close. Section 7 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 include open, high, low, and close prices as well as the number of trades and trading volume. Quote bars include closing best bid and ask and their sizes. Trade data span the period from January 1998 to July 2018. TickData only offers quote data starting from January 2010, and we extend that period to 2006 with similar data obtained from CME DataMine. We use data for the front-month contract until it reaches eight days to expiration and then switch to the next available contract. This procedure relies on the most actively traded contract and follows the industry rollover practice.[6] We exclude days when the market is closed or when the trading session ends early due to a US holiday. For most tests, the data are aggregated to one-minute or lower frequency. For the 2020 out-of-sample test, we acquire E-mini S&P and VIX futures data from FirstRate Data.

We compute one-minute log returns, using the last price for every minute. For easier interpretation, we annualize average return by multiplying period return by 252, the number of trading days in a typical year. Our results are similar if we use *simple* returns instead of *log* returns. Also, the results are almost identical if returns are computed with quote midpoints instead of trade

[5] Stroud and Johannes (2014) study how E-mini S&P return volatility changes around the clock. Muravyev and Ni (2020) show that option returns are negative at night and positive intraday. We show that night VIX futures returns are positive at night pre EU-open. Ranaldo (2009), and Breedon and Ranaldo (2013) study currency returns around the clock, and their pattern differs greatly from what we find for equities.

[6] The CME Group states on its website (link): "CME Group Equity Index futures allow market participants to roll their futures positions from one quarterly futures contract month to the next at any time they choose. However, the trading floor convention is to roll the expiring quarterly futures contract month eight calendar days before the contract expires." Also, Carchano and Pardo (2008) compare five roll criteria for stock index futures and find "no significant differences between the resultant series."

prices (see Figure IA.1 in the Internet Appendix). Futures returns offer two practical advantages for studies of equity risk premium: (1) they are already in excess of the risk-free rate, and (2) they already account for the dividends paid by S&P 500 index, unlike SPY.

The notional value of E-mini S&P 500 futures contract is $50 times the S&P 500 index level. If S&P is 1566 (sample average) then one E-mini contract represents $78,300. Following the literature, we compute the realized volatility from ten-second log returns and then annualize it. Volume is the number of contracts traded times the contract's notional value. The relative bid-ask spread is the difference between ask and bid prices scaled by the quote midpoint. Market depth is the average of the number of contracts available at the best bid and best ask.

The E-mini S&P is the most popular contract linked to the S&P 500 index. E.g., the SPDR S&P 500 ETF (ticker SPY) traded $18.5 billion per day in 2012 versus $142 billion for the E-mini S&P. SPY only trades from 6:00 am to 8:00 pm, which excludes EU-open. Similarly, a median S&P 500 stock trades only 17 times after-hour (Gregoire and Martineau, 2019); thus, studying EU-open returns for individual stocks is not feasible. Regular, or "big," S&P 500 futures were popular until early 2000s but now thinly traded. We confirm that EU-open results hold for E-mini Nasdaq 100 and E-mini DJIA that have the same trading hours as E-mini S&P futures but are less liquid.

The S&P E-mini futures were launched by the CME in 1997 and are traded exclusively on Globex. They are referred to as "mini" because their size is only 1/5 of that for regular S&P 500 contracts, and "E" because they are only traded electronically. The CME gradually extended the Globex trading hours, but until July 2003, the trading started at 1:00 am and only covered part of EU-open. We begin our sample in 2004 after the trading day was extended to almost 24-hour and overnight liquidity increased. Table IA.3 in the Internet Appendix shows how trading activity for parts of the day changed from 1998 to 2018. Deep-night activity jumped from 0.07% of all trades in 2002 to 1.28% in 2004 or 18 times in two years. Table IA.4 shows that extending our sample to an earlier period does not materially change main results.

3. Overnight liquidity

How does the trading environment change over a day? While the rules and technology stay the same, investor composition, news geography, and trading activity do change. A trading day can informally be split into three regimes – night or Asia (6:00 pm to 2:00 am ET), Europe (2:00 am to 9:30 am), and the US (9:30 am to 4:15 pm). A new CME session starts at 6:00 pm ET. The

Japanese stock market opens at 7:00 pm in winter, followed by China and Hong Kong at 8:30 pm. They remain open until 1:00, 2:00, and 3:00 am, respectively. Frankfurt and Eurex stock exchanges open at 2:00 am, followed by London and several Euronext markets at 3:00 am. Most European markets remain open until 11:30 am. The US stock market opens 9:30 am and closes at 4 pm, but trading in futures remain open and active until 4:15 pm. Most US investors leave by the start of the next trading session at 6:00 pm. Table IA.1 summarizes trading hours. The E-mini contract trades 22:45 hours a day, 5 days a week from 6:00 pm on Sunday to 5:00 pm on Friday. The continuous session spans from 6:00 pm to 4:15 pm the next day, followed by a 15-minute trading halt from 4:15 to 4:30 pm and a 30-minute session from 4:30 to 5:00 pm. All times in the paper are Eastern Time (ET) if not specified otherwise.

Market conditions differ greatly across night/Asia, Europe, and the US. Table 2 and Figure 2 show that trading activity and liquidity are expectedly lowest at night/Asia, higher during European hours, and most active during the US hours. Volatility is 56% lower for Asia and 37% lower for Europe than for the US. The entire Asian regime only contributes 14% to daily return variance. Volatility and volume are driven by many factors: risk-sharing, noise trading – price discovery is only one of them. Trading volume also varies greatly. Per-hour volume for Asia is 5.5 times lower than for Europe, which in turn is 8.4 times lower than for the US. Asian volume is relatively low compared to volatility because the S&P 500 index depends on the Asian economy, but its traders constitute a relatively small share of all investors. Indeed, the average trade size, a measure of investor clientele, is lowest during Asia (3.4 contracts); the trade size is 44% and 132% higher for Europe and the US. Perhaps investors who trade E-mini at night are smaller on average.

Although the night before EU-open is the least active, it is still abundantly liquid in absolute terms, with 121 trades and $36 million traded per minute, or $17 billion for the entire 8-hour session. Thus, even large investors can seamlessly execute their trades. The bid-ask spread is almost always one tick: 0.25 index points, or $12.50. The average spread is 0.017%. The market is deep, with on average 65 contracts at the best bid (or ask), or about $5.6 million available for immediate execution. EU-open is even more liquid as E-mini's volume jumps five-fold once Europe opens. The CME estimates that E-mini S&P futures are the 4th most actively traded index future in Asia with an average daily volume of $7.1T during Asian hours, surpassed only by Hang Seng ($15.5T ADV), KOSPI 200 ($12T), and OSE Nikkei index futures ($8.2T).

4. Market return around the clock

In this section, we study how the average market return depends on the time of day and document the EU-open puzzle. Figure 1 shows how average returns for E-mini S&P futures accumulate minute-by-minute through a day. The results are puzzling. Cumulative return remains flat (fluctuates between -1% and 1% p.a.) overnight and is slightly negative, -1.3% p.a., by 11:30 pm. But then the trend reverses; cumulative return starts to increase slowly and then accelerates shortly before European stock exchanges open at 2:00 am. The price run-up stops about 30 minutes after London opens at 3:00 am. During these four hours, from 11:30 pm to 3:30 am, cumulative return increases from -1.3% to 6.3% for a 7.6% p.a. total. The return fluctuates between 2% and -2% p.a. during the rest of European and most US hours. Volatility spikes at the US open but does not affect the average return. During the last two hours of the US hours, cumulative return increases by 4% p.a.; but due to huge volatility, the return is only statistically significant for few minutes at 3:45 pm (see Figure IA.2). This pre-close price increase almost completely reverses between US close at 4:15 pm and 6:00 pm re-open. We study this zig-zag in Section 6.

Our goal is to explore and understand the main pattern in Figure 1: why are returns high during EU-open and low during the rest of the night? With this goal in mind, we define EU-open to cover the entire period with positive returns. We explore alternative definitions for EU-open and how they line up with the uncertainty resolution hypothesis in Section IA.2.

The average market return is concentrated in the four hours between 11:30 pm and 3:30 am. The start of EU-open, 11:30 pm, corresponds to 4:30 am German Time, when the first European investors wake up and check the market. The positive return trend accelerates around 1:30 am (7:30 am in Europe) when many investors arrive at the office before the European stock market opens at 8:00 am. Returns continue to increase as London investors arrive. The second part of EU-open, when European markets open, accounts for 5.4% of the 7.6% EU-open return. Returns increase steadily with no swings. Figure IA.2 explores the statistical significance of cumulative returns during EU-open, US close, and the two periods in between. Returns become statistically significant 40 minutes into EU-open, and strongly significant around 1:30 am. US close returns become statistically significant for only a brief 20-minute period around 3:45 pm.

Table 1 compares EU-open return with the rest of the day (from 3:30 am to 11:30 pm). Average EU-open return is 7.60% p.a. with a *t*-statistic of 6.35 and a Sharpe ratio of 1.67, while the rest-of-day return is -0.8% with a *t*-statistic of -0.17.[7] EU-open appears less risky by simple risk measures. First, the return standard deviation is 4.55% p.a., 3.9 times lower than for the rest of the day. Skewness is positive (1.64), indicating that large positive returns are more likely than large negative returns, a feature that many investors prefer. In contrast, return skewness is negative for the rest of the day (-0.99) and the entire day (-0.42). This difference between EU-open and rest-of-day return skewness may help reconcile why return skewness is negative for aggregate stock market and positive for individual stocks (e.g., Albuquerque, 2012). The largest loss and gain are comparable for EU-open, -3.95% and 4.52% per day. Thus, EU-open returns are not driven by few outliers. A trading strategy based on EU-open has a maximum drawdown of only 8% versus 66.4% for the rest of the day. Kurtosis is the only measure that is higher for EU-open, 57 versus 16. Fourth return moments are similar, but EU-open volatility is much lower, and kurtosis depends on their ratio. EU-open is usually quiet with occasional large price moves. Of course, these measures may not fully reflect the risks associated with EU-open.

Figure 1 identifies main return patterns, but are any of the short-term price swings significant? EU-open stands out among all one- or four-hour windows. We compute average return and its *t*-statistic over a one-hour window, then move it by one minute and repeat. Figure 3 shows the moving average of centered *t*-statistic over a day. For negative returns, *t*-statistic touches a 5% threshold an hour before EU-open and briefly at 9:00 am, when US macro news is released. The one-hour *t*-statistic reaches six during EU-open while only two other hourly intervals briefly touch a 1% threshold: around 7:30 pm and 7:00 am. The period before US close at 3:00 pm crosses the 5% level but does not reach 1% significance. If the window is extended to four hours, EU-open remains the only significant period.

Following the literature, we assume that the expected market return can be estimated as an average of realized returns. Average returns can be sample-dependent due to high variance and time variation in expected returns. But average EU-open returns are extremely robust and consistent. Table 3 reports EU-open returns by year and compares them to the rest of the day. EU-open returns are positive and economically significant in every year. The lowest EU-open returns are 2.25% in 2017 and 4.53% p.a. in 2004 with *t*-statistics of 1.63 and 2.06; the highest returns are

[7] Throughout the paper, *t*-statistics account for heteroscedasticity and autocorrelation as in Newey and West (1986). We also compute *t*-statistics with block bootstrap. Our results become more significant with bootstrapped *t*-statistics: e.g., a 1% threshold *t*-statistic of 2.30 instead of conventional 2.58. Thus, we prefer Newey-West *t*-statistics as they are more conservative in this case.

16.24% in 2009 and 13.52% in 2015. Average EU-open returns during the first and second parts of the sample match almost exactly. Cumulative returns for EU-open accrue over the sample period in an almost straight line (Figure IA.3). These consistently positive returns help alleviate data mining and outlier concerns, which we further address with appropriate statistical procedures in Section 5.4. EU-open return volatility follows trends in the overall market volatility and is highest in 2008 and lowest in 2017. EU-open return is significant in 9 out of 15 years. The lowest rest-of-day return is expectedly in 2008 (-55.8%), while EU-open return is 9.8% in this turbulent year. Figure 4 shows cumulative return and its *t*-statistic for a two-year moving average over the sample period. EU-open returns are significant in almost any two-year window. The financial crisis does not affect them apart from higher volatility. In contrast, returns during the rest of the day vary a lot and are statistically significant only in 2017 (*t*-statistic of 2.5). The lack of significance of rest-of-day returns is not surprising because high volatility leads to wide confidence intervals.

Other robustness tests confirm that EU-open returns are consistently positive. First, EU-open returns are positive in every calendar month and weekday (Table IA.7). Return is highest on Tuesdays (9.64%) and lowest on Mondays, night after a weekend (4.83%). It is lowest in January and October (3.11% and 3.75%) and 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 2008 financial crisis. Second, EU-open results are robust to excluding (1) days with important macro or earnings announcements, (2) triple witching days, (3) days when S&P futures hit up/down limits, and (4) the turn of the month period. Interestingly on the FOMC announcement days, the famous pre-FOMC drift starts shortly into EU-open after zero return preceding night (Figure IA.9). Thus, EU-open period is important for other anomalies. Third, EU-open return decreases from 7.6% to 6.6% if we exclude its five most positive returns. Therefore, EU-open results are not driven by few outliers. The trajectories for average cumulative returns over a day computed from quote midpoints and trading prices are indistinguishable (Figure IA.1). Thus, the EU-open puzzle is not due to bid-ask bounce or other microstructure concerns. We also confirm that E-mini futures of all maturities and not just front-month contracts have an identical time-of-day return pattern as in Figure 1. Cumulative average returns for E-mini Nasdaq 100 and Dow index futures have very similar patterns to E-mini S&P returns (Figure IA.2). Finally, EU-open returns remain positive during the pre-2004 period when the market was closed during part of EU-open (Table IA.4).

Finally, we study how market returns depend on the time of the day in 2020. This paper was originally completed before the pandemic (with the sample ending in 2018). We believe that 2020 – a year of unprecedented uncertainty – provides a challenging out-of-sample test that speaks to the uncertainty resolution hypothesis. Typically, one year is too short to reliably estimate expected returns, especially during a crisis. But the 2020 results have pleasantly surprised us. Positive returns are still mainly concentrated during the EU-open period validating its boundaries. EU-open returns are especially high in the midst of the crisis in March and April 2020, consistent with the uncertainty resolution hypothesis.

In 2020, a global pandemic struck and claimed two million lives in less than a year. It created "unprecedented economic uncertainty" by causing lockdowns, production disruptions, consumption changes, and government interventions. Despite the uncertainty, the stock market had an unprecedented V-shaped recovery. We repeat the main analysis using futures data for 2020 acquired from FirstRate Data that sources its data directly from the CME. The same method as before is applied to the continuous futures series created from one-minute price bars for S&P E-mini futures (and VIX futures) between January 2 and December 31, 2020.

Panel A of Figure 5 plots the E-mini return accumulated on average over a day in 2020. For comparison, we also plot cumulative returns for the main sample in grey on the right axis and scale them 3-to-1 to match the total daily return in 2020. Returns fluctuate vigorously in 2020 due to a small sample and extreme volatility. But the return pattern for 2020 and the main sample look remarkably similar. The average return trajectories are particularly close outside of regular US hours, between 6:00 pm and 7:30 am, even the timing of local highs and lows match. Average EU-open return is 24.5% p.a. with a t-statistic of 2.3. In contrast, average return during the rest of the day is -10.2% p.a. with a t-statistic of -0.3. There is no visible zig-zag around US close which is so prominent in the main sample in Figure 1. This graph suggests that results for the main sample are unlikely due to chance. Panel B of Figure 5 shows that more than half of the cumulative EU-open return for 2020 (14.3% of 24.5%) is concentrated during the COVID market crash between February 21 and March 23. The remaining 10.2% mostly come from the first part of the post-crash recovery. In contrast, the close-to-open period excluding EU-open and the US open-to-close period lost 36.4% and 19.0% p.a., respectively, during the COVID market crash. Positive EU-open returns contrast with negative returns for other parts of the day during the crash. While the analysis of 2020 is insightful, the rest of the paper focuses on the main sample.

5. Explaining the puzzle

In this section, we try to explain the EU-open puzzle. We first show that the puzzle is driven by the European equity market open rather than the Asian close (Section 5.1). We then consider potential explanations, including uncertainty resolution (Section 5.2), limits to arbitrage (Section 5.3), data mining (Section 5.4), inventory risk, news arrival, investor sentiment, and carry costs (Section 5.5). We conclude that uncertainty resolution is most consistent with the data.

5.1 Asian close versus European open

To explain EU-open returns, we first distinguish the impact of two main recurrent events during EU-open: European equity markets open and Asian equity markets close. Intuitively, night hours are less active than European, 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, and London opens, and Hong Kong closes at 3:00 am. Daylight saving time (DST) – an exogenous shock to relative time between Europe and Asia – helps us separate the effects of Asian close and European open. Asia does not observe DST, while Europe and the US do. DST in Europe extends from the last Sunday in March to the last Sunday in October. DST in Europe and the US overlap except for a brief period of three to four weeks, depending on a year.

From the US and EU investor perspective, the Hong Kong market closes at 3:00 am ET in winter but at 2:00 am in summer. If Asia is responsible for the EU-open price run-up, it will shift with the shift in Asian time relative to Europe and the US. To test this hypothesis, Figure 6 compares cumulative returns and trading volume around EU-open during winter and summer DST in Europe. In European time, cumulative returns and volume are very similar in winter and summer. The EU-open price run-up is constant in European time and thus shifts in Asian time. Indeed, the same graphs but in Asian time clearly show a one-hour shift between summer and winter for return and volume, which are highly statistically significant. The volume pattern "lives" in European time, consistent with the European session being more liquid than pre-EU night. This return shift proves that European open and not Asian close drives the EU-open price run-up. Hence we call it "EU-open." This result encourages us to explore a special role played by European investors.

5.2 Uncertainty resolution

The uncertainty resolution hypothesis comes closest to explaining the EU-open puzzle. We first explain this hypothesis and then extensively test it. In short, European investors return to the market during EU-open after the night break; they process accumulated information and thus resolve uncertainty, which in turn increases prices. This hypothesis implies that market returns should be low throughout the night when uncertainty accumulates and high during EU-open, when uncertainty is resolved. Returns follow changes in uncertainty.

How does information translate into prices? Information includes anything that can move prices, such as patterns in related securities, proprietary data feeds, social media sentiment, and broadcasted news. Heterogeneous investors, who differ in capital and expertise, "vote" on how the arriving information should affect the S&P 500. Typically, information is processed almost instantly as a critical mass of investors monitors the market. But if the quorum is missing, then partially processed information, and thus uncertainty, will accumulate until a sufficient share of investors votes on it. Information uncertainty reflects how much market price deviates from value after a proper risk adjustment. Several theories show how higher uncertainty leads to a larger stock price discount (Hong and Wang, 2000, Easley and O'Hara, 2004; Hu et al. 2019).[8]

Uncertainty stays relatively low during the day, except it increases through the night prior to EU-open and decreases during EU-open. Many large and sophisticated investors are active during European and the US hours. But uncertainty can accumulate at night when they are away. News about the Asian economy impacts global stock markets, but its asset management industry is relatively small and does not specialize in quantifying how local news affects global stocks. As a result, E-mini prices do not fully reflect night information, and thus uncertainty accumulates until European investors arrive and act on it. Uncertainty does not disappear in an instance because EU-investors arrive gradually: some wake up early, most come in the second part of EU-open. By the time US investors arrive, Asian information is mostly reflected in E-mini prices.

A water tank analogy helps to visualize our intuition for how information is processed. Imagine information like water flows into a tank – the market. Water exits the tank via a drain, and the outflow speed proxies for investors' capacity to process information. Amount of water in the tank at any moment proxies for the information uncertainty. Most of the day, the outflow speed exceeds the inflow speed (which can vary too) with little water in the tank. However, as US investors exit for the night, the drain narrows, and water start to accumulate until European

[8] To see why, consider a stylized example where a coin toss determines the economy's future. You estimate that the probability of tossing heads, a good state, is uniformly distributed between 0.4 and 0.8, hence the uncertainty. Extra information from European investors let you conclude that the probability of heads is 0.6; uncertainty is resolved. A risk-averse investor will pay more, or require lower expected return, for the 0.6 gamble than for the 0.4–0.8 one.

investors arrive and the outflow speed increases again. The tank is nearly empty prior to US close, the water level increases through the night, until EU-open and then it gradually decreases back to nearly empty.

Several tests support the uncertainty resolution hypothesis from different angles. *First*, what if European investors skip trading, perhaps because they are on holiday? Unique EU holidays provide an exogenous shock that restricts uncertainty resolution during EU-open. If uncertainty is not being resolved, EU-open returns should be low and similar to pre-EU-open, while positive returns should shift to later in the day when US investors arrive. The data support this prediction. We collect and manually verify holiday dates from the New York Times website. We focus on days when the two main European exchanges, Frankfurt and London, are closed, but the US market 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. Of course, unique EU holidays are rare, and our sample period includes only 81 such days. Table 4 compares average returns and trading activity for holidays with the rest of the sample. E-mini futures volume and volatility drop by 54% and 19%, respectively, relative to the prior month's average; thus, much less uncertainty is resolved during EU-open on EU holidays. Remarkably, EU-open returns are slightly *negative* on EU holidays (-0.49% p.a.), but returns are positive (9.49% p.a.) later during European hours when the first US investors arrive and resolve uncertainty. This return is comparable to a 7.78% EU-open return on non-holidays.

Second, how does uncertainty change around the clock? One popular measure of uncertainty is VIX index. VIX relies on prices of S&P 500 index options, which do not trade during EU-open. Fortunately, VIX futures actively trade at night with about one billion dollars of exposure traded on a typical night. Introduced in 2004, they became popular after the 2008 financial crisis. On June 22, 2014, their trading hours were finally extended to match E-mini futures and include EU-open. We apply the same approach as for E-mini futures to this VIX futures sample (2014 to 2018).

VIX futures confirm that uncertainty increases before EU-open and decreases during EU-open. Whaley (2013), among many others, reports that daily VIX futures returns are *highly negative* and attribute them to the variance risk premium. Remarkably, we find in Table 6 that VIX returns are *positive* at night before EU-open with a cumulative return of 39.6% p.a. and a t-statistic of 2.8. Cumulative returns steadily increase except for a temporary drop during China/Hong Kong open at 8:00 pm, perhaps the open resolves some uncertainty. Cumulative returns peak around the start of EU-open, independently validating how we define this interval. VIX return during EU-open is -46.2% p.a. with a *t*-statistic of -5.2. Uncertainty decreases during EU-open and especially its second part, when European stock markets open. VIX return is highly volatile and mildly negative during the rest of the day. Figure 7 confirms these results; VIX returns are (1) positive only before EU-open, (2) negative and significant at the 1% level only during EU-open, (3) negative but rarely statistically significant for the rest of the day. EU-open VIX returns are negative and 1% significant in every two-year period (Figure IA.5). The patterns in VIX futures returns remain significant after we control for the so-called leverage effect (a strong negative correlation between stock returns and VIX changes, Figure IA.10). Similar to E-mini S&P, the time-of-day pattern for VIX futures returns holds out-of-sample in 2020. The cumulative return is 23.1% p.a. before EU-open, and then it drops by 30.8% to -7.7% during EU-open. Information uncertainty increases before EU-open and then decreases rapidly during EU-open.

Third, high uncertainty predicts higher future EU-open returns. Information uncertainty is high if a lot of information arrives overnight as measured by high volume and volatility. Indeed, Table 5 shows that EU-open returns are higher after high volatility or volume during night pre-EU-open. Also, controlling for them, EU-open returns do not significantly depend on volatility or volume of the previous US session as US investors had a chance to process this information. For example, the overnight volume has a *t*-statistic of 3.3 versus 1.3 for the US volume.

Fourth, high uncertainty, as measured by VIX or its daily change, predicts a higher EU-open return. Table IA.6 shows that the 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 a *t*-statistic of 4.1, and VIX level has a *t*-statistic of 1.2, consistent with investors mainly reacting to changes in uncertainty.

Next, textual uncertainty measures also predict EU-open returns. The daily news-based economic policy uncertainty index by Baker et al. (2016) counts the frequency of articles in US newspapers that contain uncertainty keywords about the economy and government. Twitter-based economic and market uncertainty indices by Baker et al. (2020) are based on all tweets sent on Twitter since January 2010 that contain keywords related to uncertainty, the economy, or equity markets. Finally, we add one non-textual measure, VSTOXX implied volatility on EURO STOXX 50 index (Europe's leading blue-chip index), that captures European uncertainty. Table 5 shows that uncertainty increases as reflected by these four indices or their daily changes predict higher EU-open returns. In univariate regressions, all eight specifications have a positive coefficient, and seven out of eight are statistically significant; VSTOXX level has a *t*-statistics of 1.4. Daily changes in these four alternative uncertainty indices remain significant after controlling for VIX.

The *last two* tests indirectly support the uncertainty resolution hypothesis. Figure 2 shows that the trade size is smallest at night, but it increases by 43% during EU open. Perhaps Asian investors trade in a smaller size, and European investors indeed arrive during EU-open. Finally, prices become 14% more informationally efficient during EU-open. A variance ratio test assesses price efficiency (Amihud and Mendelson, 1987) and shows that prices are least efficient at night – the variance ratio is higher pre-EU-open than post-EU-open. Variance at time *t* is computed as an average of squared 24-hour returns from *t* to *t+24h* over all days. Figure IA.11 shows a ratio of variance at time *t* to the overall daily average for all starting times. The variance ratio at the start of EU-open is 1.08, or 8% higher than average, and it drops to 0.95 by the end of EU-open.

Finally, we explore alternative definitions of the EU-open period in Section IA.2. In short, European investors are more likely to arrive during the second part of EU-open and especially around the Frankfurt and London open. As uncertainty resolution accelerates during these times, and returns accumulate faster as the uncertainty discount shrinks. The consistent results for the alternative periods help alleviate the concern about how we define EU-open.

5.3 Limits to arbitrage and trading strategy

Limits to arbitrage may prevent investors from taking advantage of market anomalies. In this section, we explore the after-cost profitability of a trading strategy that buys E-mini futures before EU-open and closes the position at its end. This strategy (1) is highly profitable after conservative estimates of trading costs and (2) has enough capacity to earn $50 million per year. Furthermore, (3) the naïve strategy can be greatly improved by only trading on days with high uncertainty pre- EU-open, generating a much higher out-of-sample R^2 than comparable strategies that predict market return.

We estimate costs conservatively by taking a perspective of a small impatient investor who pays (i) the exchange fees and commissions and (ii) the entire bid-ask spread by buying at the ask and selling at the bid. The spread is almost always one tick, or $12.5 per contract, with large depth at the best bid and ask. We use trades to identify prevailing bid and ask prices that almost always match the actual bid and ask for the shorter sample with available quotes. Our estimates of costs are conservative because, in practice, execution algorithms optimally provide and take liquidity with executions that are only slightly worse than the midquote (e.g., Anand, Irvine, Puckett, and Venkataraman, 2012). We assume that fees and commissions are \$2.50 per roundtrip (rt) per contract, or 1/5 of the tick, most of which are the CME exchange fees. Active investors can reduce exchange fees and commissions to less than \$1.0/rt by owning or leasing a CME member seat.[9]

Panel A of Table 7 reports returns of the baseline strategy with and without trading costs. Before costs, the strategy makes a 7.76% annualized return with a Sharpe ratio of 1.65. The after-costs profitability is expectedly lower; the average return declines to 2.6% with Sharpe ratio of 0.55. Nevertheless, the return remains statistically significant, and the after-cost Sharpe ratio is higher than 0.36 for a buy-and-hold strategy that holds an all-day long position with no costs.

The baseline strategy with conservative costs sets a lower bound for the after-cost profits. It can be substantially improved by only trading on days with higher than average returns. To implement this conditional strategy, we estimate a linear model that predicts EU-open returns out-of-sample. The model only relies on two ex-ante predictors: (1) daily change in VIX (4:15 pm to 4:15 pm) and (2) realized volatility at night pre-EU-open (6:00 pm to 11:30 pm), which are motivated by the uncertainty resolution hypothesis. To focus on out-of-sample, the estimated coefficients from the first year (2004) are used to forecast EU-open returns daily for the next month (1/2005). We then repeat the steps: expand the estimation window by a month, re-estimate the model, and apply it to the next month.

This simple model works remarkably well. The out-of-sample R^2, computed as in Campbell and Thompson (2008), is 6.57% and is stable over the sample period (Figure IA.8). The out-of-sample R^2 is only slightly smaller than an in-sample R^2 of 7.49%. For comparison, Gao et al. (2018) predict intraday returns for SPY ETF and find an R^2 of 2.6%, which they characterize as "a level that exceeds typical predictive R^2 s at the monthly frequency." We compute out-of-sample forecasts for EU-open returns with the predictive model and trade on days when the ex-ante forecast exceeds 1.5 times total transaction costs. The strategy trades on 2 out of 5 days, and trading frequency is relatively stable over time. The strategy can be further improved by reducing trading costs or sizing trades proportional to forecasted returns.

[9]The CME exchange fees for trading E-mini at Globex for non-members increased to \$2.36/rt by 2018. Small hedge funds 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. A one-time membership application fee is \$2000.

The conditional strategy is almost as profitable as the baseline that trades every day. Its cumulative return is 6.76% per year before costs compared to 7.76% for the baseline, despite trading on only 40% of days. Thus, EU-open returns are low on no-trade days, 1.07% p.a. per-trade costs do not change, but total costs are lower as the strategy trades on fewer days. The conditional strategy picks days with more than double the average returns, while trading costs are similar across days. The after-cost return is 4.61% with a *t*-statistic of 4.6. Its Sharpe ratio of 1.20 is in the same range as the pre-cost Sharpe ratio for the baseline strategy (1.65). Figure IA.7 shows cumulative returns for baseline and conditional strategies over time.

How much capital can these strategies take? How well do average returns translate into dollar profits? Acquiring large positions causes a price impact that is hard to estimate from the public data. Still, these data can provide useful insights subject to simplifying assumptions. Capponi, Menkveld, and Zhang (2019) estimate that execution algorithms can trade up to 10% of the average total volume without price impact. Relying on this number, we assume that a strategy can buy 10% of trading volume each minute at the ask price. The estimated capacity is approximately linear in this parameter. The position is accumulated over a four-hour window from 9:30 pm to 1:30 am by a standard VWAP algorithm that buys 10% of recorded volume at the ask minute-by-minute. The position is closed with a similar VWAP algorithm that starts at the end of EU-open (3:30 am) and usually ends within an hour. In practice, risk managers enforce limits on traders' positions. Thus, we also consider a constrained strategy variation, which caps the maximum position size on days with extreme volume. EU-open strategies take large positions and make high dollar profits on these days. We prefer the constrained strategy, which is more conservative as it limits profits on such days.

Panels B of Table 7 reports the capacity and profitability for the strategies. The conditional strategy often trades on high volume days and thus acquires a larger average position: $9.3 billion of S&P 500 exposure versus $6.9 billion for the baseline strategy. Investors can deploy significant capital into these strategies. The EU-open strategy has no analogs in academic literature, but its capacity can be compared to the short-term reversal strategy in US equities that has an estimated break-even capacity of $9 billion (Frazzini, Israel, and Moskowitz, 2012). The EU-open strategies earn large after-cost profits. The baseline strategy earns before- and after-cost profits of $80 and $40 million per year, while the conditional strategy earns $60 and $50 million pre-costs and post-costs. The unconstrained version of the strategy earns three times higher annual profits. These estimates provide a starting point for evaluating EU-open tradability.

Finally, even long-term investors can benefit from high EU-open returns. They can reduce trading costs by timing trades. If a long-term investor wants to buy (sell), the best time is before (after) EU-open; investors benefit from high EU-open return as they are not compensated for holding market risk during the rest of the day.

5.4 Data mining and data snooping

Can pure luck explain high EU-open returns and zero returns during the rest of the night? Several results are particularly useful for addressing data mining concerns. EU-open returns are positive in every year of the 14.5-year sample. The lowest annual return is as high as 2.25%, with a *t*-statistics of 1.6 in 2017. A skeptical reader can pick and drop any ten calendar years and, yet, EU-open returns remain significant in the remaining "worst" 4.5 years. Returns remain large in the 2020 out-of-sample test. VIX futures returns in Section 5.2 provide another out-of-sample test.

The concern is that perhaps the "true" expected return for EU-open is not high, and another intraday period is responsible for positive night returns. First, average realized returns could differ from expected returns. Maybe EU-open (rest-of-night) returns have been unexpectedly high (low). Second, we focus on four hours with the highest return. In a regression of realized returns on four-hour indicators, EU-open can be highly significant just by chance. In this classic multiple testing problem, *p*-values should be adjusted for implicitly taking the maximum over all four-hour periods.

Fortunately, well-developed statistical tests help evaluate how picking the best performing period affects our results, from the Bonferroni adjustment to White (2000) bootstrap reality check. The Bonferroni correction is the most conservative such a test. It assumes that a maximum is selected over multiple independent hypotheses, and a *p*-value must be multiplied by the number of hypotheses. If the regular *p*-value is 1% with ten hypotheses, then the adjusted *p*-value is 10%. EU-open return has a *t*-statistic of 6.35 with a *p*-value of 10^{-10}. Even if we consider all four-hour intervals with a half-hour step, the adjusted *p*-value is 2×24 times higher but still remains well below the 1% significance level (5×10^{-8}). The Bonferroni correction is conservative because these four-hour periods overlap and are not independent. The main result also easily passes less conservative tests such as Romano and Wolf (2005) or Hansen, Lunde, and Nason (2011).

White's (2000) reality check is another popular test that uses bootstrap to preserve dependencies in the data. First, returns are demeaned by subtracting the average return for each minute across all days because average returns are zero under the null hypothesis. Second, we bootstrap a return sample of the same size as the original data by sampling trading days with replacement to preserve the intraday correlations as in block bootstrap. We identify a one-hour (four-hour) period with the highest *t*-statistic in the bootstrapped sample and record it. After repeating this step 10,000 times, we construct a bootstrapped distribution of maximum *t*-statistic under the null hypothesis of zero expected return. A 99% percentile of this *t*-statistic distribution equals 4.0 (3.7) for one-hour (four-hour) horizons, much higher than the conventional threshold of 2.57. With *t*-statistic of 6.35, EU-open easily passes the White's reality check. Finally, the 4.0 threshold is more conservative than the *t*-statistic levels that the literature on false discoveries suggests for evaluating equity cross-sectional anomalies (e.g., Harvey, Liu, and Zhu, 2016).

5.5 Other explanations

We consider other explanations. Conventional risk-based theories attribute expected returns to higher risk as reflected by market volatility, negative price jumps, and negative skewness, among other measures. But EU-open is less risky compared to the rest of the day according to these measures. The peso problem cannot explain why EU-open returns are positive in every year and differ so much from returns in adjacent intervals. Perhaps close-to-open stock returns are positive because most news arrives at night. Indeed, market-moving US news such as earnings announcements and much macro news is released shortly before the US open or after US close. But EU-open occurs while the US is in the deep night, which is at least five hours away from these news intensive periods. Even most European macro news is announced after EU-open's end. High-frequency trading (HFT) have been widely adopted during our sample period, but average EU-open returns didn't change much and thus are unlikely to be impacted by the growth of HFT.

Inventory risk and illiquidity premium affect returns because liquidity providers, who are risk-averse and have limited capital, absorb customer order flow and must be compensated for holding suboptimal portfolios. Perhaps night-averse investors sell at US close and buy back at EU-open. We extensively test this hypothesis. First, the market return must be high during every night hour to compensate dealers for the risk, but the return is zero or slightly negative between US close and EU-open. Second, the market is closed on weekends but they have slightly lower EU-open returns than weekdays. Third, if no inventory shock occurs at US close, then high EU-open returns should disappear. But EU-open returns remain large for the subsample with zero order imbalance. Finally, inventory risk is subsumed by uncertainty resolution in a direct horse race. Order imbalance from US close ceases to predict EU-open return once we control for VIX change, which remains highly significant. Section IA.3 explains these results in detail.

An investor sentiment hypothesis argues that European investors are buying at the open because they are more optimistic than everyone else. We study how EU-open return depends on measures of investor sentiment, including the bull-bear sentiment from the AAII investor survey (a proxy for the sentiment of US retail investor), Baker and Wurgler (2006) index (a 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 IA.6 except for Michigan consumer sentiment that is significant at the 10% level.

Carry costs, which include interest and margin payments and security lending fees, are typically incurred at night although not necessarily during EU-open. Perhaps higher overnight market returns compensate investors for the costs. Carry costs are usually proportional to interest rates, but Table IA.6 shows that EU-open returns do not depend on them. Also, most carry costs are incurred every calendar day and are higher on weekends, but EU-open returns are slightly lower over weekends, although the difference is not significant (Figure IA.12 and Table IA.7).

6. Zig-zag around the US close

In this section, we explore the zig-zag at the US close, which is the second significant return pattern in Figure 1. The cumulative returns increase by 6.1% p.a. on average between 2:00 pm and 3:45 pm reaching a peak and then drop by 5.4% between 3:45 pm and 6:00 pm. Thus, the net return is close to zero. But if we assume that investors can time the peak perfectly and define the zig-zag return as the up return minus the down return, then the average zig-zag return is 11.5% p.a. with a *t*-statistic of 4.4 and a Sharpe ratio of 1.17 (Panel A of Table 8). The zig-zag appears robust over time except for the last two years of the sample (0.2% in 2017 and -6.2% in 2018), and usually both zig-zag legs contribute to the total return. E-mini returns are typically negatively autocorrelated (Johnson, 2016), and thus it may seem that high returns during the zig revert during the zag. However, the up and down returns are in fact positively correlated (9%).

Several hypotheses can at least partially explain the zig-zag. First, limits of arbitrage can explain why it is not arbitraged away. Investors, who trade the zig-zag, pay the spread twice, on the way up and on the way down. Zig-zag returns drop from 11.5% to mere 1.0% p.a. after transaction costs, which are computed as in Section 5.3. Also, the average pre-cost returns decrease to 5.7% in the second part of the sample, making it even less attractive for arbitrageurs.

Second, data mining can also play a role. The "true" returns may differ from the historical average because we picked the best performing zig-zag. We define the zig-zag to maximize its return during our sample, but its profitability drops drastically if the timing is slightly off. If the peak is moved by just ten minutes from 3:45 pm to 3:35 or 3:55 pm, then zig-zag returns drop by about almost half from 11.5% to 7.7% and 5.3%, respectively. Thus, the returns are sensitive to small design changes.

Third, the uncertainty resolution hypothesis can partially explain the downward portion of the zig-zag. Bogousslavsky and Muravyev (2021) show that the closing auction in the US equity market attracts massive volume from passive investors. Similarly, Bogousslavsky (2021) argues that daytime arbitrageurs tend to unwind their leveraged positions just prior to the US close. This unwinding causes greater mispricing and thus information uncertainty. This increase in uncertainty near the US close triggers negative average returns that correspond to the downward portion of the zig-zag in Figure 1. The uncertainty created by the US close is ultimately resolved at EU-open together with the rest of accumulated overnight uncertainty. According to this hypothesis, US-close returns should predict EU-open returns on the next day. Indeed, US-close return (3:45 to 4:00 pm) negatively predicts EU-open return with a *t*-statistic of -4.1. We also study how zig-zag returns depend on measures of uncertainty and other predictors. Consistent with the uncertainty hypothesis, the zig-zag returns are higher when uncertainty is high as measured by VIX or realized volatility (relative to monthly average). These two variables are the only significant predictors of zig-zag returns with *t*-statistics of 2.0 and 2.2 (Panel B of Table 8), respectively. However, all variables become insignificant, and R^2 drops from 2.0% to 0.2%, if 10% of days with highest VIX are dropped. Thus, the conditional predictability is concentrated during the high VIX period.

Finally, Bogousslavsky (2020), Akbas et al. (2021), and Lou et al. (2018) note that average negative open-to-close US returns tend to reverse (i.e., increase) just before the US close. This reversal can be driven by day traders, who often close their short positions (i.e., buy) just before the US close to avoid overnight risk. These positive returns can coincide with the upward part of the zig-zag. Unfortunately, we do not have enough statistical power to properly test this hypothesis, as none of the variables that we tried significantly predict returns during the upward portion.

Overall, these results do not let us pin down one specific explanation for the zig-zag.

7. Conclusion

In this paper, we introduce and explain a new puzzle about the average market return. We use prices of E-mini S&P futures that are actively traded around the clock to study how excess returns for the S&P 500 index depend on the time of day. One period clearly stands out: 100% of the average market return is concentrated in four hours between 11:30 pm and 3:30 am ET, which is a deep night in the US and an early morning in Europe. EU-open returns are robust, highly significant, and have an impressive Sharpe ratio. A strategy of buying/selling futures before/after EU-open is profitable net of conservative estimates of trading costs and has a large capacity.

Using daylight savings time as an exogenous shock to relative time between Europe and Asia, we show that the EU-open price run-up is driven by the European open rather than the Asian close. The EU-open puzzle is difficult to explain, but resolution of information uncertainty is the most promising explanation. Usually, investors quickly process arriving information and keep prices close to value. But during deep night pre-EU-open, a critical mass of investors is missing causing uncertainty to accumulate through the night. As European investors arrive during EU-open and process the accumulated information, uncertainty is resolved, and prices increase. Uncertainty resolution can explain low returns before EU-open and high returns during EU-open. Several tests, most notably EU-open returns on unique EU holidays and overnight VIX future returns, support this hypothesis. Zero market returns during regular hours remain a puzzle.

Our results have several implications. First, information uncertainty arises naturally in financial markets, and its resolution is an important determinant of average market returns. Second, the market's ability to absorb arriving information can be limited at night because a critical mass of investors is missing. Third, European investors are often neglected, but they play the key role in resolving uncertainty that accumulates overnight. Thus, they potentially serve as marginal investors. Finally, the average market return has an "atomistic" structure where it is positive during EU-open and some macro news such as FOMC announcements but zero most of the time. Hopefully, future research can shed light on why observed average returns are atomistic.

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

This table reports the main statistics for E-mini S&P futures returns, including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. These measures are computed from annualized log returns (the period return times 252) and, when applicable, are reported as a percent. E.g., the average return during EU-open is 7.60% annualized. We also report return distribution percentiles, which are not annualized. E.g., the minimum return during EU-open is -3.95% per day. 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 adjusted for heteroskedasticity and autocorrelation.

	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, % p.a.	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

Table 2

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 regular trading hours (6:00 pm to 4:15 pm) and is split into the night before 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 4:15 pm). 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 the bid and ask prices normalized by the quote midpoint and is reported in basis points. Market Depth = 0.5 × (Best Bid Size + Best Ask Size).

	EU-open	Night 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, $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
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, b.p.	1.71	1.71	1.71	1.71	1.69	1.70
Market depth, $M	6.2	5.6	5.5	10.8	34.3	16.0

Table 3
Returns by year

This table reports the main statistics for E-mini S&P futures returns by year. The statistics include average return, standard deviation, and *t*-statistics. These statistics are based on annualized log returns and, when applicable, are reported as a percent. E.g., the average return during EU-open in 2004 is 4.53% p.a.. 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 adjusted for heteroskedasticity and autocorrelation. The last row reports the 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 4
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 ("after EU-open"). Normalized volume and volatility are computed relative to their prior monthly average. Unique EU holidays include days when London or Frankfurt stock exchanges are closed, but the US stock market is open, 81 events in total. The last two columns report the difference between the two samples and *t*-statistic, which is adjusted for autocorrelation and heteroskedasticity.

	EU Holidays	Rest of sample	Difference	*t*-stat. for difference	Relative change
Return, EU-open, %	-0.49	7.78	-8.27	[-2.2]	
Return, after EU-open, %	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 5
Conditional EU-open returns

This table shows how market returns during EU-open depend on lagged market conditions. Panel A includes short-term predictors based on the Asian session before EU-open and the previous US session. Column (1) includes VIX index and its change from the previous close. Columns (2) and (3) include shocks to log volume and volatility during these two periods. I.e., volume relative to its two-week average for the same period. Panel B report the coefficient and *t*-statistic of a univariate regression of EU-open return on lagged daily change in uncertainty (Column 2) or uncertainty level (Column 3). The measures include VSTOXX (implied volatility on EURO STOXX 50 index), the news-based economic policy uncertainty index by Baker et al. (2016), and Twitter-based economic uncertainty (TEU) and market uncertainty (TEU) indices by Baker et al. (2020). The last column reports the number of observations for each variable. *t*-statistic is adjusted for autocorrelation and heteroskedasticity.

Panel A. Market-based uncertainty measures

	EU-open return				
	(1)		(2)		(3)
VIX change	0.0970***	Volume, Asia	0.1282***	Volatility, Asia	0.3660***
	[4.1]		[3.3]		[3.0]
VIX	0.0054	Volume, US	0.0714	Volatility, US	0.2589*
	[1.2]		[1.3]		[1.8]
Intercept	-0.0235		-0.125**		-0.539***
	[-0.3]		[-2.0]		[-2.8]
R^2	0.062		0.013		0.021
Num. Obs.	3,653		3,645		3,645

Panel B. Other uncertainty measures

Uncertainty measure	Change	Level	Num. Obs.
Economic policy uncertainty	0.0009**	0.0014**	3,653
	[2.0]	[2.2]	
Twitter economic uncertainty	0.0003**	0.0004**	1,900
	[2.5]	[2.2]	
Twitter market uncertainty	0.0004***	0.0007***	1,900
	[2.7]	[3.2]	
VSTOXX index	0.0650***	0.0066	3,057
	[3.0]	[1.4]	

Table 6

VIX futures returns during EU-open and other intervals

This table reports the main statistics for VIX futures returns, including return average, *t*-statistic, standard deviation, Sharpe ratio, skewness, and kurtosis. These measures are computed from annualized log returns. E.g., the average return during EU-open is -46.26% p.a. The entire trading day (last column) is split into the night before EU-open, EU-open, the rest of the day until US close ("post-EU-open"), and the period around US close. *t*-statistic is adjusted for autocorrelation and heteroskedasticity.

	Night pre-EU-open	EU-open	Post-EU-open	US-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

Table 7
Trading strategy

Panel A reports the 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 reports 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 is 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 the 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. Trading capacity and profits for strategy with accumulation window

	No constraints		Position constraints	
Strategy	P&L, $M p.a.	Position size, $B	P&L, $M p.a.	Position size, $B
Baseline, no TC, %	200	7.41	80	6.92
Baseline, with TC, %	170	7.41	40	6.92
Conditional, no TC, %	190	10.52	60	9.29
Conditional, with TC, %	170	10.52	50	9.29

Table 8
Zig-zag around the US close
This table reports the main statistics (Panel A) and conditional regressions (Panel B) for zig-zag returns around the US close. Zig-zag return is defined as return between 2:00 pm and 3:45 pm ("up" part) minus return between 3:45 and 6:00 pm ("down" part). We report summary statistics for the full zig-zag, its up and down parts, and alternative zig-zag definitions with the top at 3:35 or 3:55 pm instead of 3:45 pm. "Net-of-Costs" column reports zig-zag returns net of transaction costs. These measures are computed from annualized log returns. E.g., the average zig-zag return is 11.55% p.a. In Panel B, we study how zig-zag returns depend on predictors including VIX at 2 pm, VIX change between prior close and 2 pm, realized volatility between 9:30 am and 2 pm normalized by its monthly average, return between 9:30 am and 2 pm. The last column focuses on the subsample that exclude days with VIX > 28% (top 10% of VIX). *t*-statistic is adjusted for heteroskedasticity and autocorrelation.

Panel A. Zig-zag average returns

	Full	Up	Down	Net-of-Costs	Top point 3:35	Top point 3:55
Average return, % p.a.	11.55	6.11	-5.44	0.98	7.76	5.30
t-statistic	4.45	2.81	-3.36	0.38	3.04	2.08
Standard deviation, % p.a.	9.88	8.28	6.17	9.88	9.71	9.72
Sharpe ratio, p.a.	1.17	0.74	-0.88	0.10	0.80	0.55
Skewness	0.90	1.18	-1.48	0.85	1.27	0.95
Kurtosis	28.84	40.35	30.10	28.81	27.21	25.80

Panel B. Zig-zag conditional returns

	Full	Up	Down	Full, VIX<28
VIX	0.0203**	0.0158*	-0.0045	0.0042
	[2.2]	[1.8]	[-0.8]	[0.8]
VIX change	0.0346	-0.0581	-0.0926**	-0.0407
	[0.5]	[-1.0]	[-2.5]	[-1.2]
Volatility, norm.	0.5666**	0.1292	-0.4374**	-0.0812
	[2.0]	[0.5]	[-2.3]	[-0.5]
Return	0.0733*	0.0173	-0.0560*	-0.0116
	[1.9]	[0.5]	[-1.9]	[-0.4]
Intercept	-0.8223**	-0.3572	0.4651**	0.0728
	[-2.5]	[-1.1]	[2.2]	[0.4]
R^2	2.0%	1.5%	2.4%	0.2%
Num. Obs.	3,623	3,623	3,623	3,268

Figure 2

Trading activity and liquidity around the clock

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

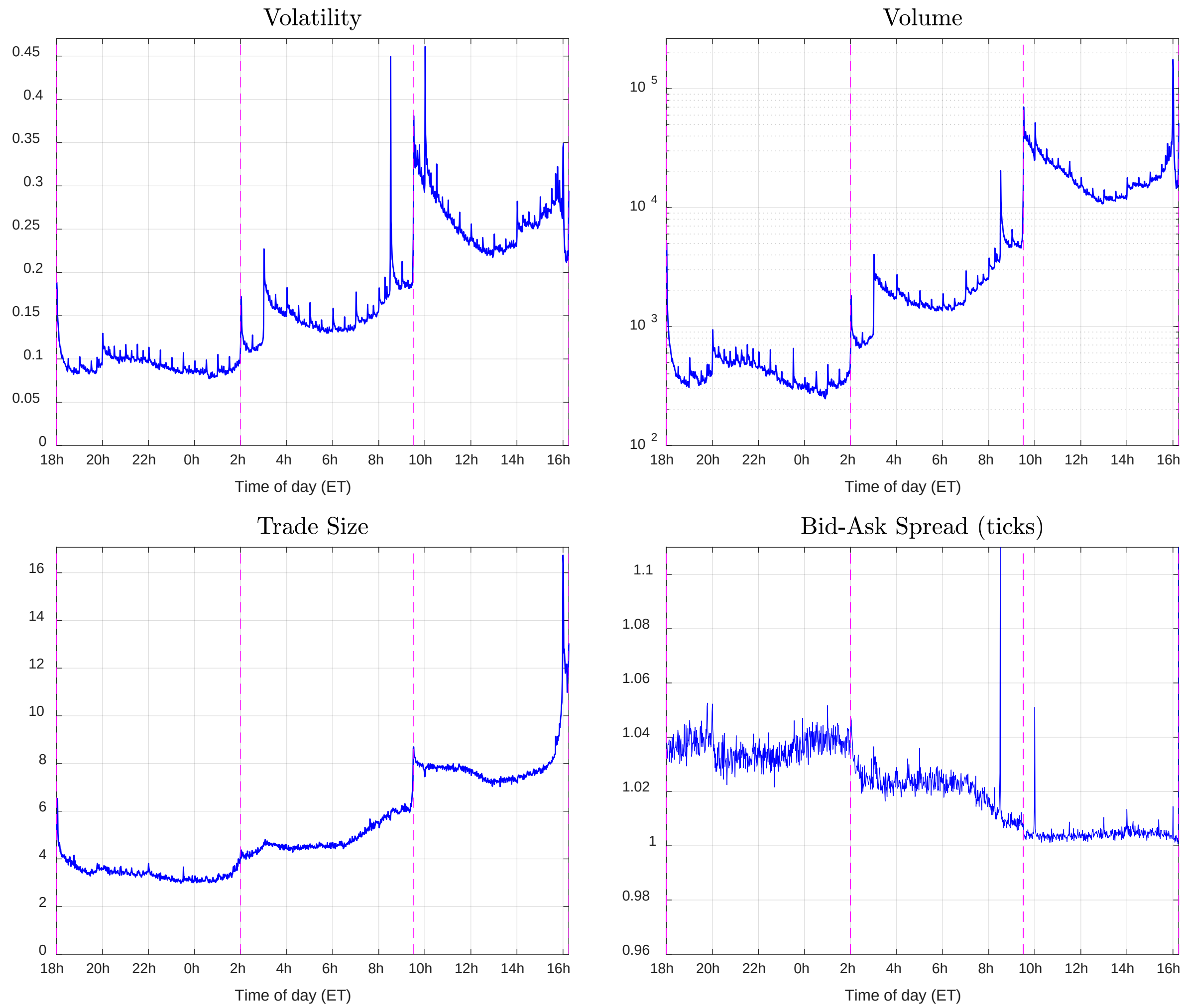


Figure 3
What other intervals have significant returns?

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

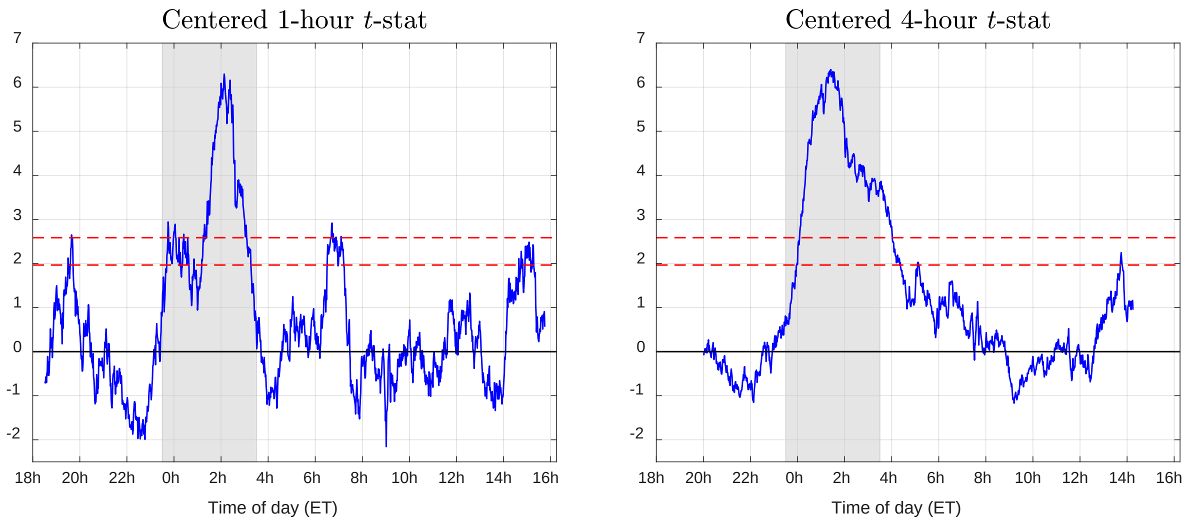


Figure 4

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

The 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). The 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 adjusted for heteroscedasticity and autocorrelation. Market return is computed from E-mini S&P future prices.

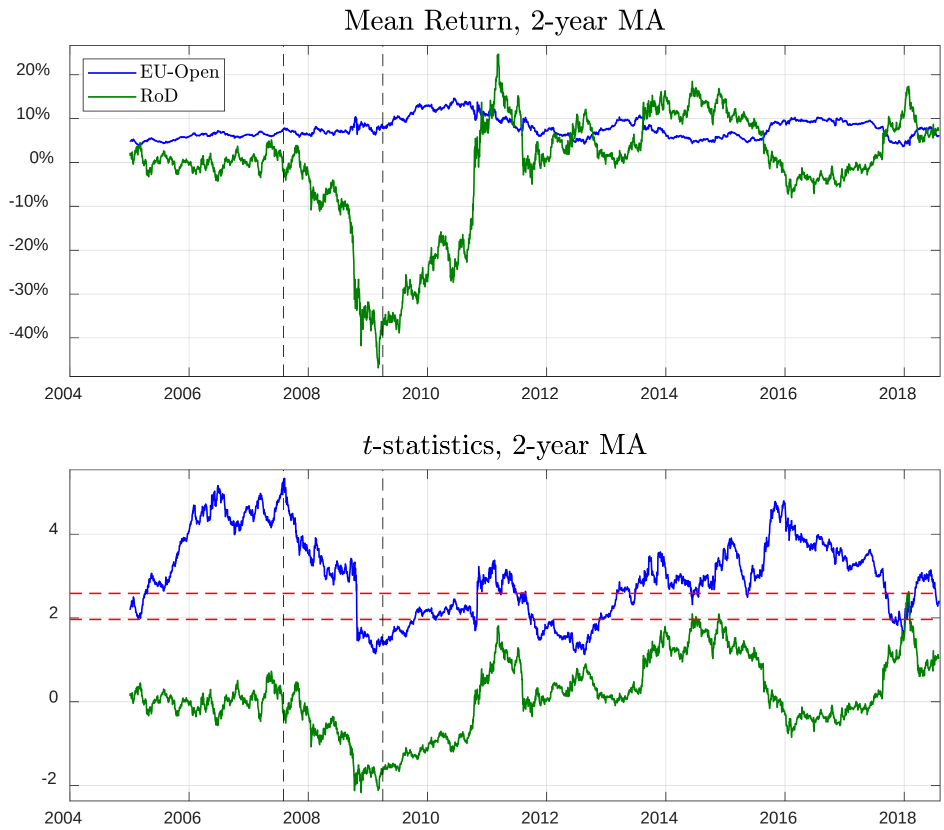


Figure 5

Time-of-day returns in 2020, the COVID crisis

Top panel shows average cumulative returns for S&P 500 E-mini futures as a function of time of the day in 2020 (in blue). For comparison, we report the cumulative returns for the main sample in pale grey on the right axis, which are scaled three-to-one to match average return in 2020. Annualized return equals the period return times 252. Bottom panel compares how returns accumulate over time for EU-open (blue, 11:30 pm to 3:30 am) and the rest-of-day (green, 3:30 am to 11:30 pm). Vertical dashed lines denote the top and bottom of the market on February 21 and March 23.

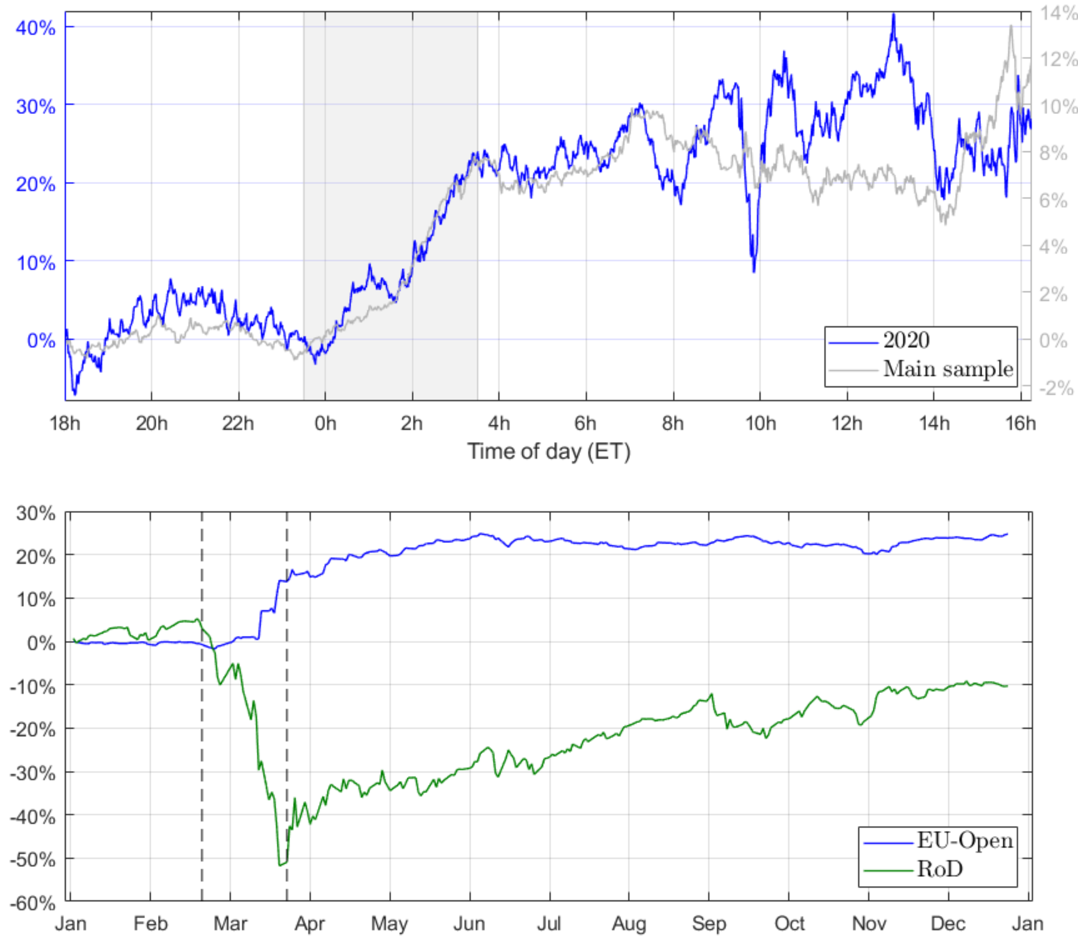


Figure 6

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. The top panel reports results in US time (ET), while the 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 the 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.

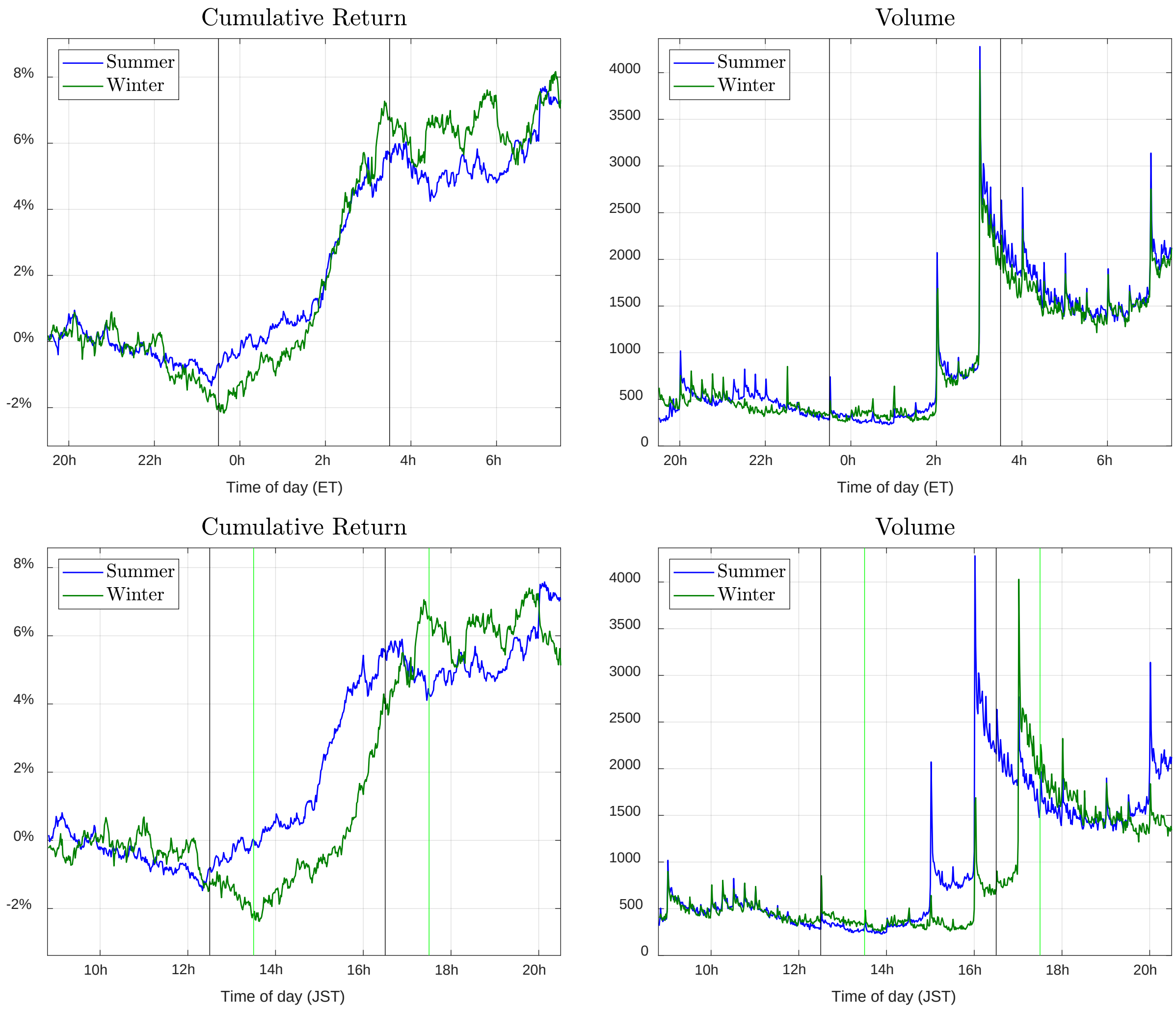
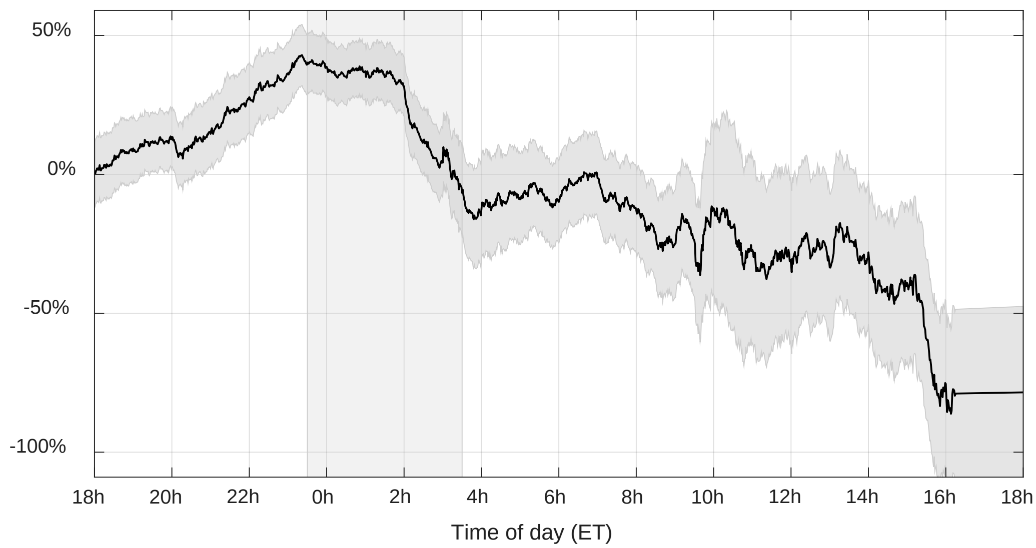


Figure 7

VIX futures returns around the clock

The figure shows annualized (average cumulative log) returns for VIX futures as a function of time of the day in Eastern Time (ET). The band around returns reflects two standard deviations for returns over a prior hour. The straight line from 4:15 to 6:00 pm denotes a single return as the market is only open for 30-minutes. The EU-open period is in grey. Annualized return equals the period return times 252. The sample period is from June 22, 2014 (first day then extended trading hours start spanning EU-open) to July 2018. The EU-open period is shaded grey.



Internet Appendix to

Market Return Around the Clock: A Puzzle

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August 25, 2021

This appendix describes how volatility, volume, and liquidity change over a day (Section IA.1), explores alternative definitions for EU-open period (Section IA.2), tests the inventory risk hypothesis (Section IA.3), and presents additional figures and tables.

IA.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 2 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 the US open as US investors arrive at 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

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first spike when Frankfurt opens. Then, volume quickly reverts to the Asian level. However, a much bigger spike occurs during the 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 the relation 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.

IA.2 Alternative definitions of EU-open

In this section, we explore how the uncertainty resolution hypothesis links investor arrival, uncertainty, and returns while also exploring alternative definitions of the EU-open period. European investors are more likely to arrive during (i) the second part of EU-open and (ii) especially around the opening time for the Frankfurt and London exchanges. Uncertainty resolution accelerates during these times, and returns accumulate faster as the uncertainty discount shrinks. The consistent results for the two alternative periods help alleviate the concern about how we define EU-open.

We confirm this prediction for (i) and (ii). First, many European investors arrive around 2:00 am ET (8:00 am EU time) when the Frankfurt exchange opens. Indeed, E-mini trading volume spikes around this time. Table IA.8 shows that the results for the main uncertainty tests are stronger for one hour from 1:30 am to 2:30 am. This hour accounts for 5.0% of the 7.6% total EU-open S&P return and for -23% of the -46% total EU-open VIX futures return. This hour also accounts for about half of the magnitude for how uncertainty measures, including VIX change, pre-EU-open volume and volatility, and Twitter uncertainty index, predict future returns during EU-open.

Second, while some investors rush to trade as soon as they wake up (during the first part of EU-open that ends at 7:30 am EU time), most European investors arrive in the second part of EU-open, after 7:30 am EU time, around the time when major EU equity markets open. Indeed, Table IA.5 confirms that volume, volatility, and trade size are 3.5 times, 36%, and 33% larger in the second part of EU-open than in the first part. Table IA.8 shows that the second part accounts for most of EU-open's uncertainty resolution and market return – a -41.7% VIX return and a 5.9% S&P return. Market return during the second part strongly depends on uncertainty measures, while this relation is positive but not significant for the first part.

IA.3 Inventory risk

What if some investors are averse to the overnight period because of lower liquidity or fear that the market moves while they are away? To avoid this period, investors can hedge or not carry positions overnight. They will pay a premium to liquidity providers for taking this risk. Inventory risk arises because liquidity providers are risk-averse and have limited capital. They are required to take customer order flow and thus hold suboptimal portfolios. The premium for inventory risk increases in undesired position size, asset volatility, dealer's risk aversion, and expected holding period. This idea goes back to at least Stoll (1978). E.g., Bessembinder (1992) shows that returns for some futures vary with the net holdings of hedgers after controlling for systematic risk. Overnight returns should be positive even without trading because equities are in positive net supply – whoever carries positions overnight is compensated for the overnight risk. According to this channel, average returns should be positive every hour during the night, including EU-open, which is rejected by the data.

The effect of inventory risk on average return should not be confused with its effect on price reversal. If investors buy at the close, their price pressure causes positive returns that subsequently reverse overnight. The price increase at the close must be offset by the price reversal overnight on average for a zero net return. If the two price impacts do not match, prices can be manipulated. Alternatively, if investors sell at the close, closing return will be negative, followed by a positive overnight reversal, including EU-open. Inventory risk implies a price reversal after an inventory shock at the close. But, its net effect on the average return is zero. Dealers can properly estimate expected imbalances (e.g., if investors repeatedly buy at EU-open) from 15 years of daily data. Only unexpected imbalances, which are 50/50 buy/sell under rational expectations, have price impact, and thus the net effect of these imbalances on the average return is zero.

Inventory risk seems intuitive and plausible, but this hypothesis struggles to explain *average* EU-open returns. Its predictions do not line up with the data. Inventory risk models cannot explain why dealers are compensated only during EU-open. Overnight return must be highly positive in every single night hour; instead, dealers lose money because of a slightly negative return in the pre-EU-open period, -1.25% p.a. in Table IA.1 and Figure 1. An opportunistic investor, who carries no inventory risk, can earn the same EU-open return as the dealers by "cutting the line" and buying right before EU-open. Section 5.3 shows that this strategy is profitable after costs. The free-rider can boost returns by buying at the bid as she loses nothing if the limit order is not executed. Thus, inventory risk cannot explain negative pre-EU-open returns combined with large positive EU-open returns, but uncertainty resolution can.

Perhaps inventory risk is priced because night is highly illiquid, and investors have to wait until European open to adjust their positions. But waiting until EU-open is a waste of time. With an average volume of 2.4 billion dollars per hour, the pre-EU-open period can accommodate large trades. Waiting until EU-open does not reduce trading costs for small trades as the bid-ask spread is almost always one tick with $5.6 million at the best bid or ask. E-mini trading is fully electronic, and trade execution can be automated either in-house or with broker-supplied algorithms.

We directly test whether the inability to trade at night or its perceived illiquidity affects overnight returns. First, while investors can trade on a regular night, the E-mini market is closed on the weekend from 4:15 pm on Friday to 6:00 pm on Sunday. Thus, the inventory risk premium should be larger over weekends than on weekday nights. Figure IA.12 compares cumulative return and volume on weekdays and weekends. Weekend returns are noisier as they are four times less frequent. If anything, EU-open returns are lower on weekends than on the other days, 4.8% versus 8.2%. Non-trading periods do not carry a higher premium in our sample.

We further test whether night illiquidity leads to a higher premium for inventory risk by comparing the earlier and later parts of the sample, pre- and post- 2011. The overnight liquidity increased substantially during the sample period. Figure IA.13 shows that while volume remained unchanged during the US hours, it doubled for Europe and quadrupled for Asia. Overnight liquidity improved, but the trajectories for cumulative returns during the first and second parts are remarkably similar through the entire night, including EU-open. Returns diverge only during the US hours, due to the effect of the financial crisis in the pre-2011 period. Overnight liquidity does not affect EU-open return, contrary to the inventory risk hypothesis.

We also study inventory shocks directly. If dealers receive no inventory shock at US close, as reflected by zero order imbalance, then high EU-open returns should disappear without price pressure at the close. But EU-open returns remain large for the subsample with a zero order imbalance. Following Easley, Lopez de Prado, and O'Hara (2016), we estimate order imbalance with a block volume classification approach using 10-second bars and tick rule. We rank days by their order imbalance during the last hour of the US session and compute next-day EU-open return for two samples with low order imbalance: with order imbalance between 25% and 75% percentiles and with imbalance between 40% and 60%. Panel A of Table IA.9 confirms that imbalance is only 0.4% for two samples. EU-open returns are large – 6.70% and 8.44% for the 25-75 and 40-60 samples – statically significant, and close to the full sample average (7.6%). Pre-EU-open returns are slightly negative. Figure IA.8 shows that the cumulative returns over the day for the 40-60 sample are similar to the full-sample returns in Figure 1. Although order imbalance might explain return reversal, it does not affect the average EU-open returns.

Finally, in a direct horse race, inventory risk is subsumed by uncertainty resolution. Inventory risk implies that order imbalance at US close predicts return reversal at EU-open. We compute order imbalance and VIX change – common proxies for inventory risk and uncertainty resolution – during the last hour of the US session. Panel B of Table IA.9 shows that both variables predict the EU-open return in univariate regressions (imbalance has a much lower R^2, 1.9% versus 7.2%). But in a joint regression, the coefficient for order imbalance becomes almost zero with a *t*-statistic of -0.3, while VIX change has a *t*-statistic of 3.1. Overall, uncertainty resolution explains return reversal at EU-open better than inventory risk.

Table IA.1
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 the 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 the US extends from the second Sunday in March to the first Sunday 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 IA.2
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. These measures are computed from annualized log returns and, when applicable, are reported as a 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 (6:00 pm), 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 6:00 pm-11:30 pm	EU-open 1st Half 11:30 pm-1:30 am	EU-open 2nd Half 1:30 am-3:30 am	Asia 6:00 pm-2:00 am	Europe 2:00 am-9:30 am	US 9:30 am-4:15 pm	Post US-close 4:15 pm-6:00 pm	Total 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 IA.3
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 the 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, 000s				Percentage of total		
	Asia	Europe	US	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 IA.4
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. Prior to 2004, the Asian session was very illiquid (see Table IA.3). Prior to July 2003, E-mini S&P only traded starting from 1:00 am. That is, the Asian session was open for only one hour instead of usual 8 hours, and EU-open was open for 2.5 hours instead of 4 hours. After July 2003, the trading hours were extended to the current 6:00 pm. The reported statistics include average return, *t*-statistics, standard deviation, and Sharpe ratio. The statistics are based on annualized log returns (the period return times 252) and, when applicable, are reported as a percent. The last two rows report average per-year statistics. 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*-statistics are adjusted for heteroskedasticity and autocorrelation.

	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 IA.5

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 June 22, 2014 to July 2018 for VIX futures. We also report the difference between the two periods and *t*-statistic for the difference, which is adjusted 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

Table IA.6
How do EU-open returns depend on market variables?

We show how EU-open return depends on macro variables measured at the previous close: VIX index, short-term Treasury rate, term spread (the difference between long-term and short-term rates), TED spread (the difference between one-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. *t*-statistic accounts for heteroskedasticity and autocorrelation.

	EU-open return
VIX	0.0168**
	[2.2]
Treasury bill	0.0079
	[0.8]
Term spread	0.0076
	[0.4]
TED spread	-0.1518
	[-1.6]
Retail invest sent.	-0.0836
	[-0.7]
BW sent.	0.1534
	[1.2]
UMich. consumer sent.	0.0048*
	[1.8]
Weekend	-0.0306
	[-0.9]
Intercept	-0.5834
	[1.6]
R^2	0.017
Num. Obs.	3,654

Table IA.7
Returns by weekday and calendar month

This table reports the main statistics for E-mini S&P futures returns by day of the week (Panel A) and by calendar month (Panel B), including the average return, *t*-statistics, standard deviation, and Sharpe ratio. They are based on annualized log returns (the period return times 252) and, when applicable, are reported as a percent. E.g., the average EU-open return on Monday (over the weekend) 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 adjusted for heteroskedasticity and autocorrelation. The last row reports the 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 IA.8
Alternative definitions of EU-open

The table reports the results for the main uncertainty resolution tests for EU-open ("Full", four hours) and its alternative definitions. We consider one hour centered on the opening of EU stock market ("Middle," 1:30 to 2:30 am), the first part (11:30 pm to 1:30 am), and the second part (1:30 to 3:30 am). The first set of rows reports return averages for E-mini S&P and VIX futures and the corresponding *t*-statistics in brackets. The second set of rows reports univariate regressions of return during a given EU-open subperiod on an uncertainty measure. The predictors include VIX change on a prior day, shocks to log volume, and volatility during night pre-EU-open, Twitter-based economic uncertainty index (TEU) by Baker, Bloom, Davis, and Renault (2020) on prior close. *t*-statistic is adjusted for autocorrelation and heteroskedasticity.

	EU-open			
	Full	Middle	1st Part	2d Part
	11:30-3:30	1:30-2:30	11:30-1:30	1:30-3:30
Return, E-mini S&P	0.0761***	0.0508***	0.0169**	0.0591***
	[6.4]	[6.2]	[2.5]	[5.9]
Return, VIX Futures	-0.463***	-0.230***	-0.046	-0.417***
	[-5.2]	[-5.2]	[-0.8]	[-5.0]
Univariate Regressions, Dep. Variable: S&P Return				
VIX Change	0.0998***	0.0375***	0.0162	0.0836***
	[4.1]	[2.6]	[1.3]	[4.6]
Volume, pre-EU-open	0.1397***	0.0883***	-0.0063	0.1460***
	[3.5]	[2.8]	[-0.2]	[4.0]
Volatility, pre-EU-open	0.4569***	0.2564***	0.0178	0.4391***
	[3.3]	[3.0]	[0.2]	[4.2]
Twitter Uncertainty	0.0007***	0.0003***	0.0002*	0.0005***
	[3.2]	[2.7]	[1.8]	[3.2]

Table IA.9
Inventory risk and EU-open return

Panel A. Zero order imbalance sample

This table shows that EU-open returns remain large after no inventory risk shock at US close. We rank order imbalance during the last hour of the US regular trading hours and form two samples, corresponding to 25% to 75% and 40% to 60% of order imbalance (50% is the median imbalance, which is close to zero). We then compute average returns and the corresponding *t*-statistic on the next day for EU-open and the overnight session before it.

Order imbalance		Pre-EU-open		EU-open	
Percentile	Average OI, %	Return, %	t-stat	Return, %	t-stat
25% - 75%	0.40%	-0.78	-0.44	6.70	4.69
40% - 60%	0.42%	-4.39	-1.37	8.44	3.39

Panel B. Uncertainty or price pressure?

This table conducts a direct horse race between inventory risk and uncertainty resolution. It shows how EU-open returns depend on a change in VIX and order imbalance at US close (from 3:15 pm to 4:15 pm). Control variables in the last column are measured at the previous close and include short-term Treasury rate, term spread, TED spread, bull-bear spread from AAII Investor Sentiment Survey, Baker and Wurgler (2006) sentiment, University of Michigan consumer sentiment index, and a weekend indicator. *t*-statistic is adjusted for autocorrelation and heteroskedasticity. The sample is smaller due to the availability of intraday VIX index data.

	EU-open return			
	(1)	(2)	(3)	(4)
VIX change	0.3089***		0.3027***	0.3031***
	[3.7]		[3.1]	[3.1]
Order imbalance		-1.1016***	**-0.091**	-0.0691
		[-5.8]	[-0.3]	[-0.3]
Controls	-	-	-	+
Intercept	0.0813***	0.0743***	0.0812***	0.0163
	[5.5]	[5.0]	[5.5]	[0.1]
R^2	0.072	0.019	0.072	0.077
Num. Obs.	2,675	2,675	2,675	2,675

Figure IA.1

Cumulative returns: quote midpoint versus trade price

Average cumulative log returns for E-mini S&P futures over the trading day. For the red line, returns are computed with trading prices as in Figure 1. For the blue line, returns are computed from quote midpoints. The two lines are barely distinguishable. The sample period is from 2006 to 2018 due to the availability of quote data.

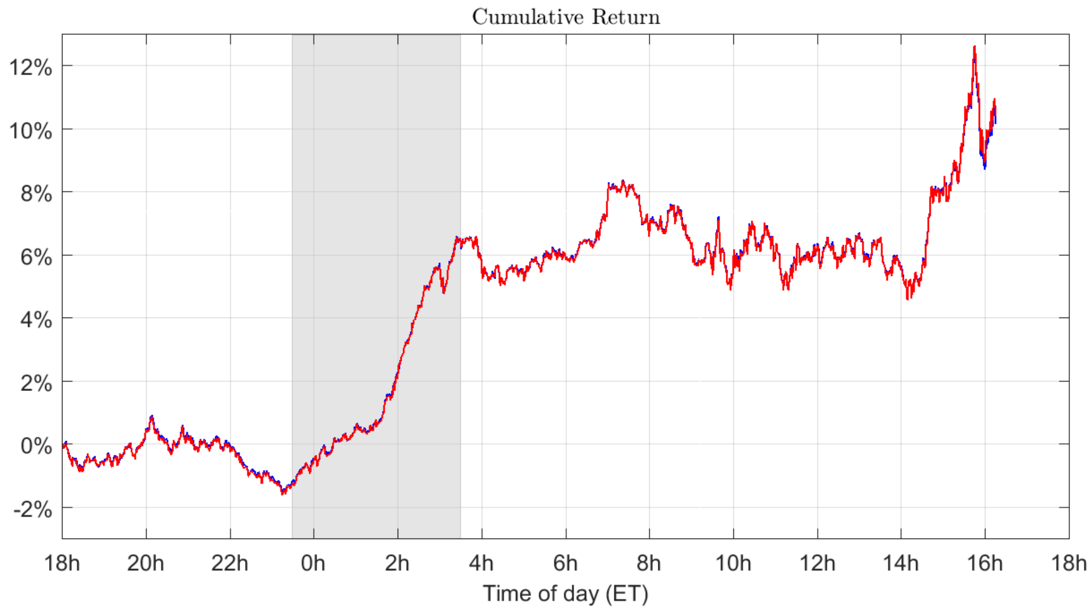
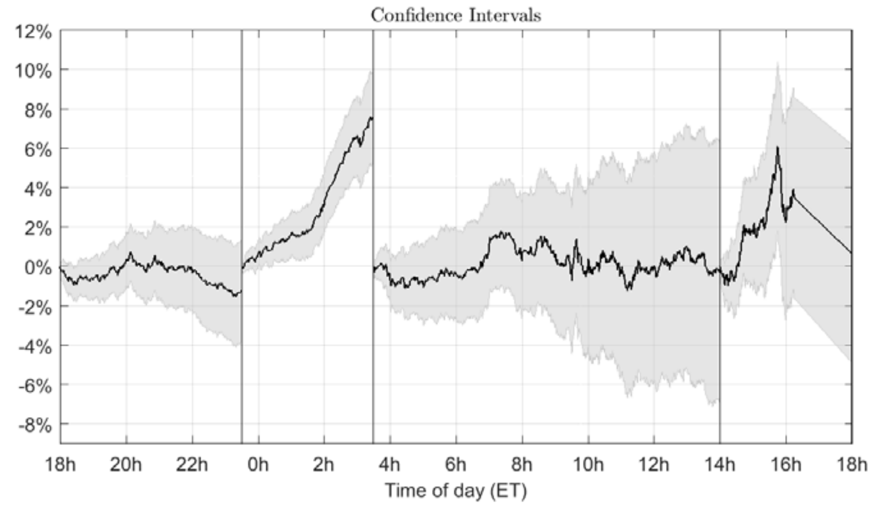
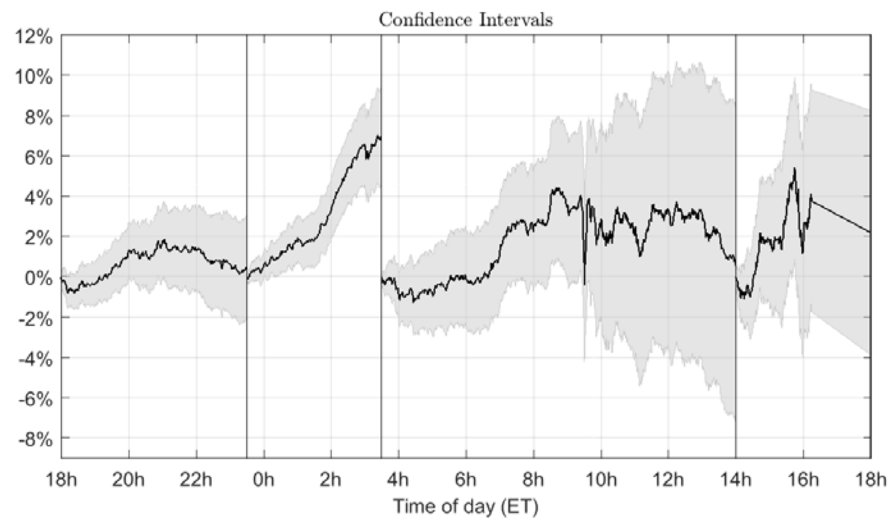


Figure IA.2
Returns for E-mini S&P 500, Nasdaq 100, and Dow index futures
This figure shows how cumulative return varies over a day with corresponding 95%-confidence intervals in grey. The day is split into four intervals: 6:00 pm to 11:30 pm (Asia pre-EU-open), 11:30 pm to 3:30 am (EU-open), 3:30 am 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.

Panel A. E-mini S&P 500



Panel B. E-mini Nasdaq 100



Panel C. E-mini Dow

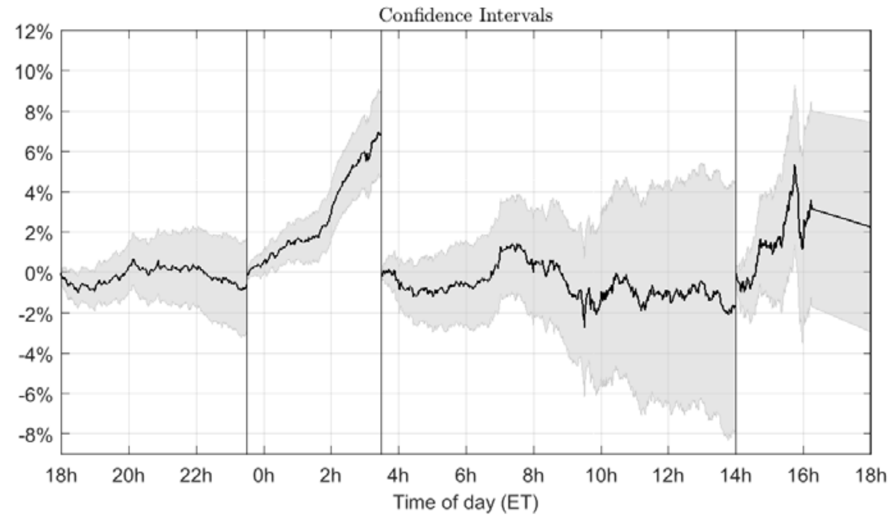


Figure IA.3
Cumulative market returns over time

The 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). The bottom panel shows the 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. The thick red line shows a two-year moving average. Market return is computed from E-mini S&P future prices.

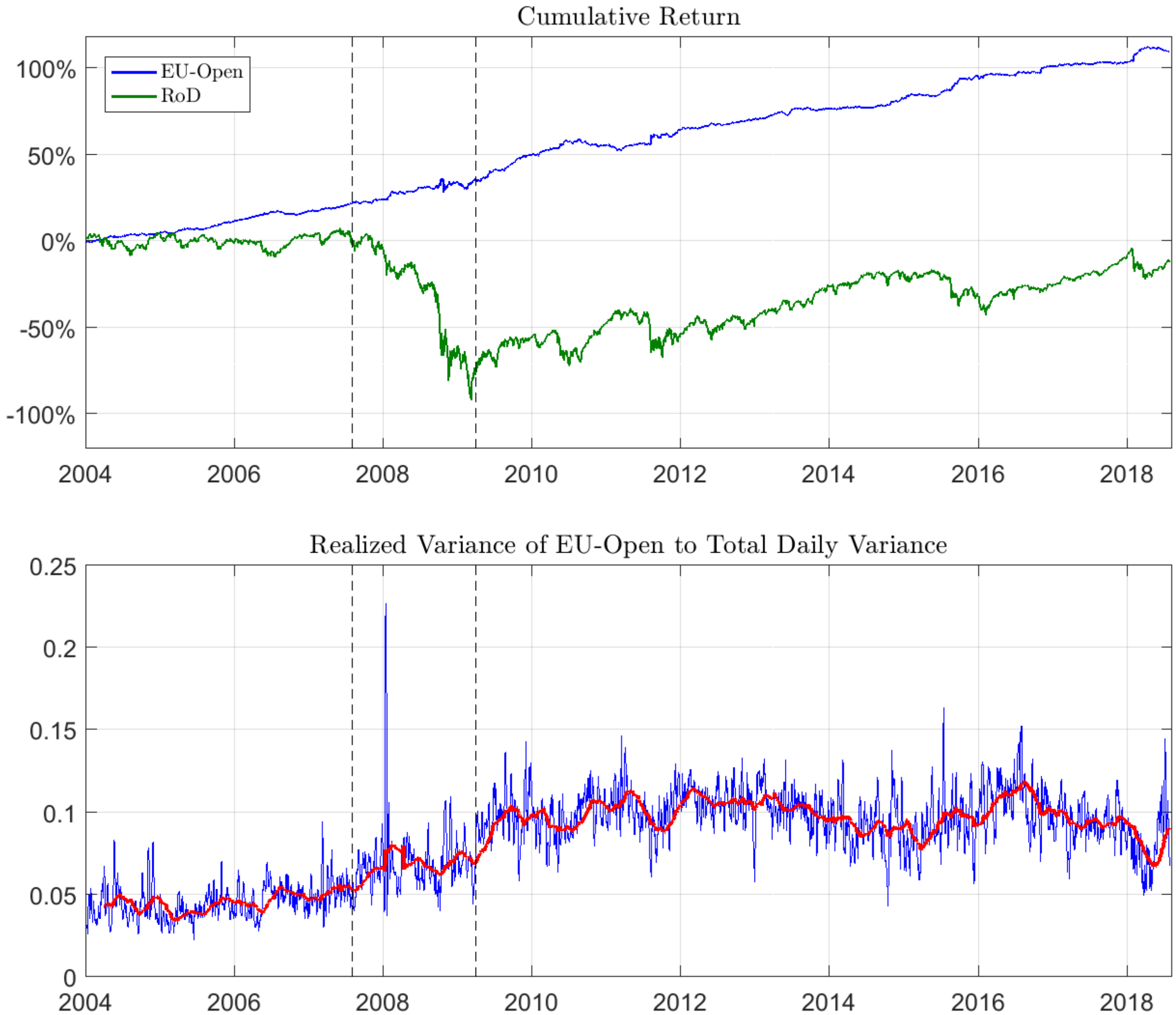


Figure IA.4

Cumulative returns for VIX futures over the sample period

This figure the 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 June 22, 2014 to July 2018.

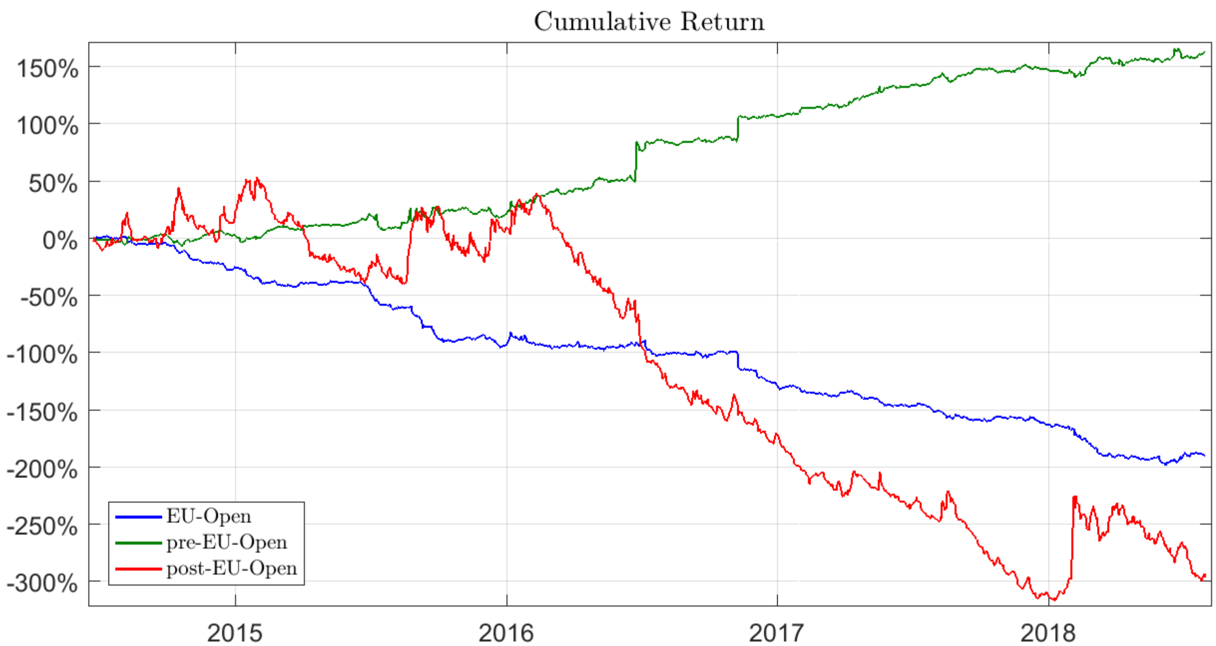


Figure IA.5

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

The top panel shows a two-year moving average for cumulative VIX future return for the 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. The 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 adjusted for heteroscedasticity and autocorrelation. Log return is computed from front-month VIX future prices.

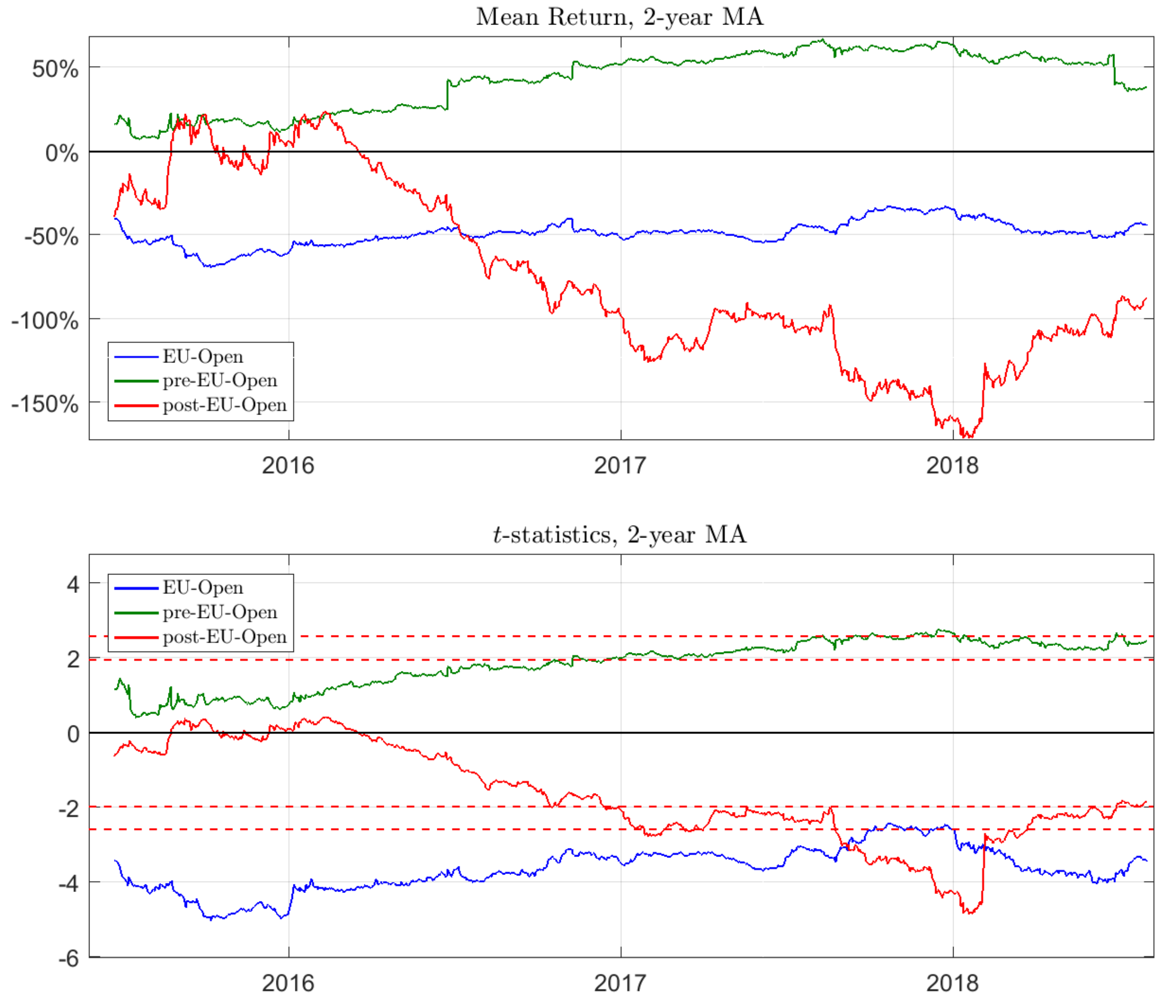


Figure IA.6
Cumulative returns for sample with zero order imbalance
This figure shows cumulative market return over a trading day for the sample with close-to-zero order imbalance on the prior US close. We compute order imbalance during one hour prior to US close (3:15 pm to 4:15 pm) and pick days that are between 40% and 60% (they thus have low order imbalance). Order imbalance is between -1 and 1 and is a proxy for inventory shocks at US close. 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; solid lines mark the EU-open period.

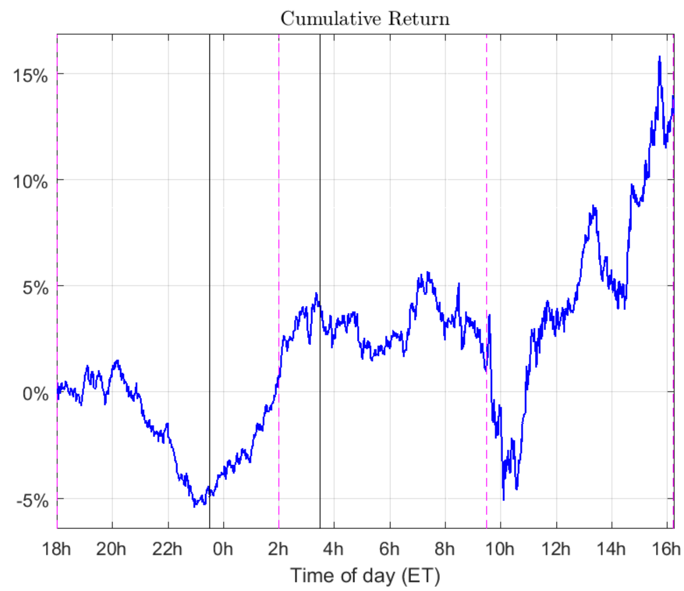


Figure IA.7

Cumulative returns for baseline and conditional strategies over time

The strategy buys E-mini future at the start of EU-open and closes a position at the end of EU-open. The 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.

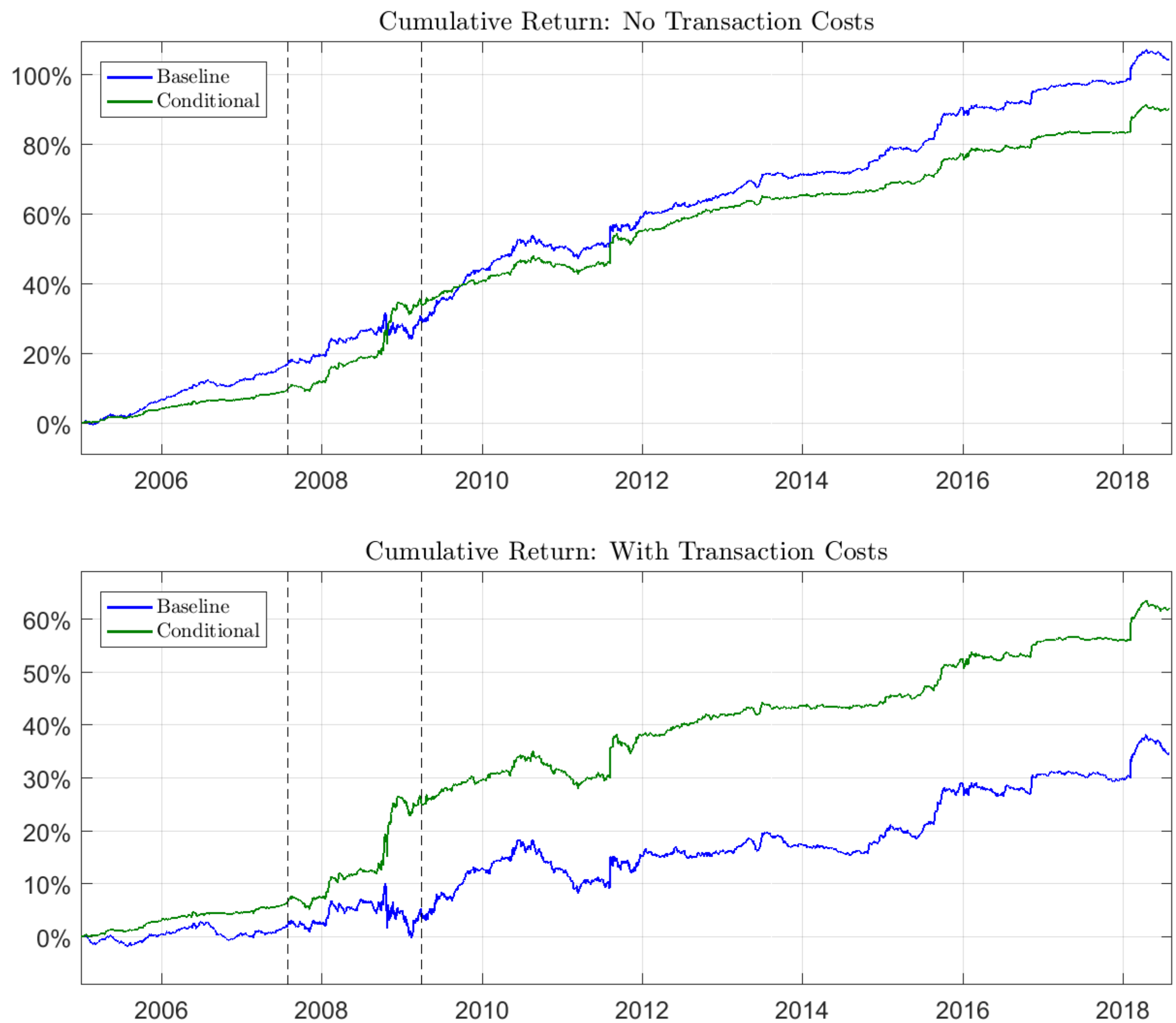


Figure IA.8

Conditional trading strategy

The figure shows the R^2 of the predictive model (left panel) and a fraction of days when the conditional strategy trades (right panel). The model uses the daily change in VIX and pre-EU-open volatility as predictors. 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.

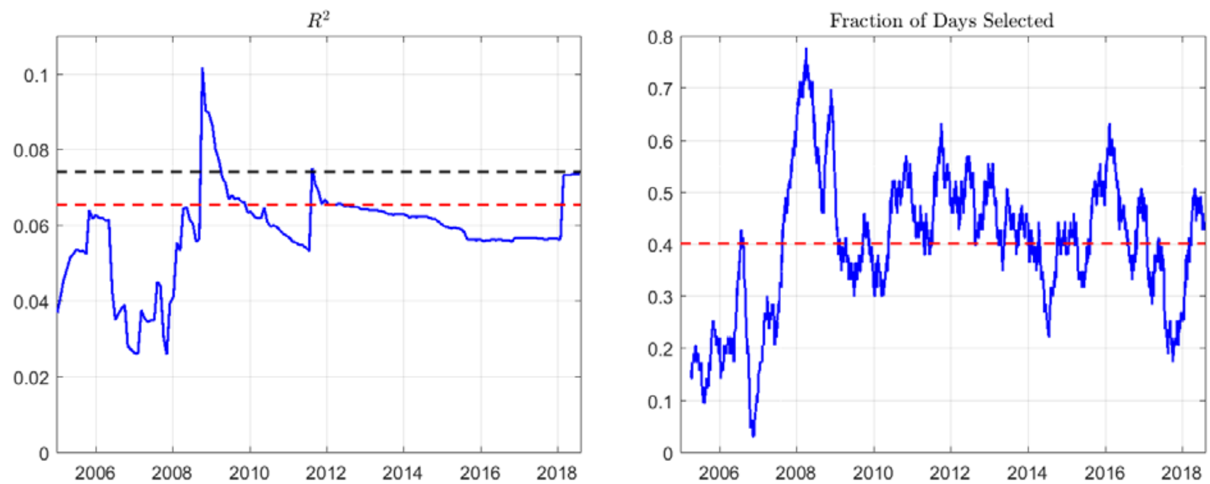


Figure IA.9

Market return on FOMC announcement days.

The figure shows average cumulative market return (from S&P 500 E-mini futures) as a function of time of the day (in ET). We annualize return as period return times eight, the number of FOMC announcements in a year. FOMC statement released at or a few minutes after 2:15 p.m. ET. Dashed lines denote Frankfurt open, US open and close. Solid black lines denote EU-open. The sample period is from January 2004 to July 2018.

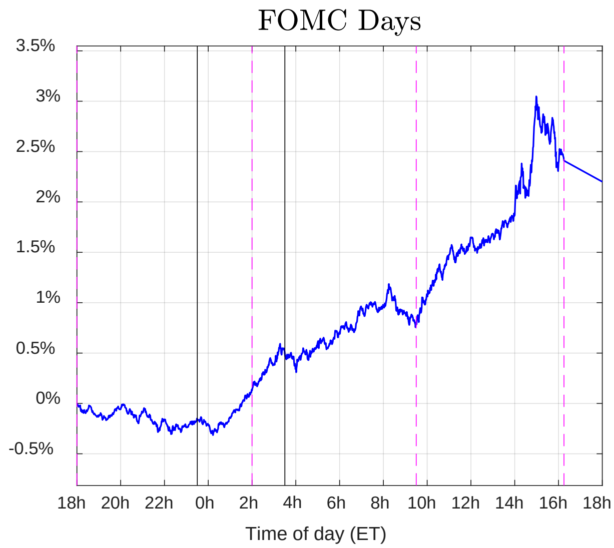


Figure IA.10

Cumulative VIX futures returns net of the leverage effect.

The figure shows how cumulative S&P-adjusted return for VIX futures varies over a day. We estimate beta of VIX futures with respect to the S&P E-mini return in a daily return regression. The two returns have a correlation of -0.85 (beta is -5.01) confirming a very strong leverage effect. We then adjust VIX futures returns to form a market-neutral strategy (VX-hedged). By construction, this strategy has zero correlation with S&P E-mini return at the daily frequency. Cumulative return is annualized by multiplying the period return by 252. Extended hours for VIX futures start spanning EU-open on June 22, 2014, and the sample ends in July 2018.

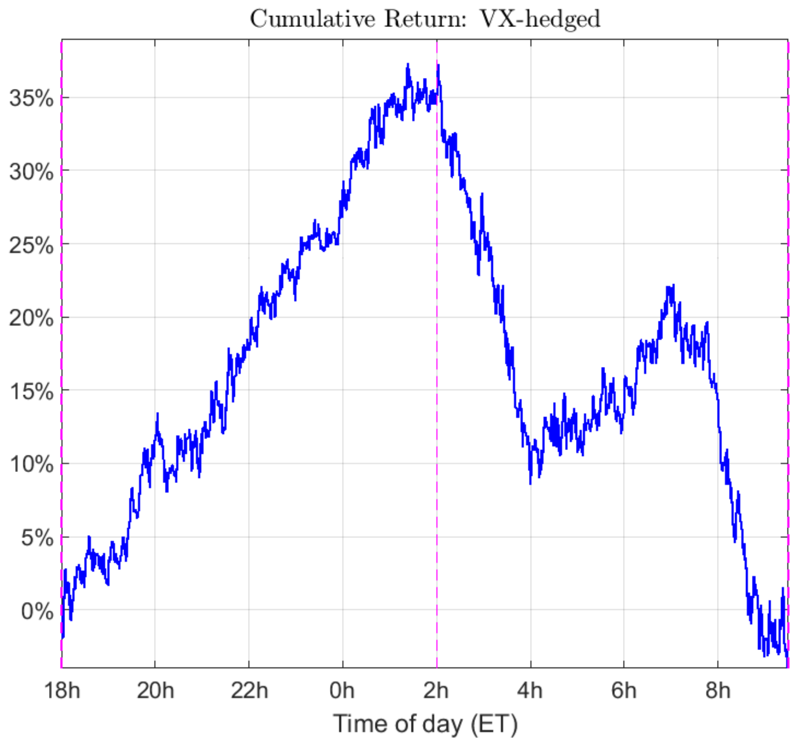


Figure IA.11

Variance ratio price efficiency test

This figure shows how the variance ratio depends on the time of the day. Higher ratio means less efficient prices. Variance at time *t* is computed as the average over all days of squared returns from *t* to *t+24h*. The figure shows the ratio of variance at time *t* to the overall daily average over all starting times. For example, the ratio of 1.08 at 0:00 means that variance is 8% higher than average for the 18:00-to-18:00 returns.

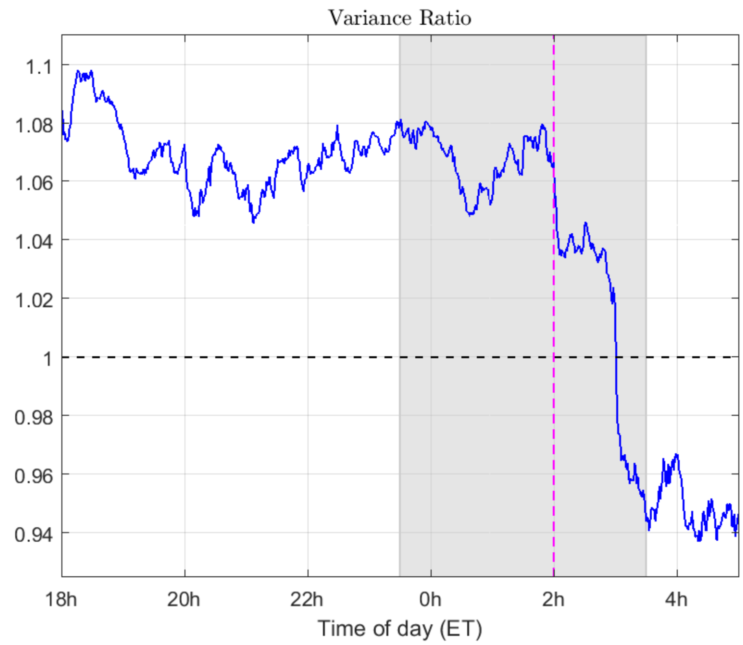


Figure IA.12
Weekends versus weekdays
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for weekends (Mon, Friday-to-Monday) with regular weekdays (non-Mon). There is little difference between the two. Cumulative return is annualized. Solid vertical dashed lines mark the EU-open period boundaries. Vertical dashed lines separate the three trading sessions.

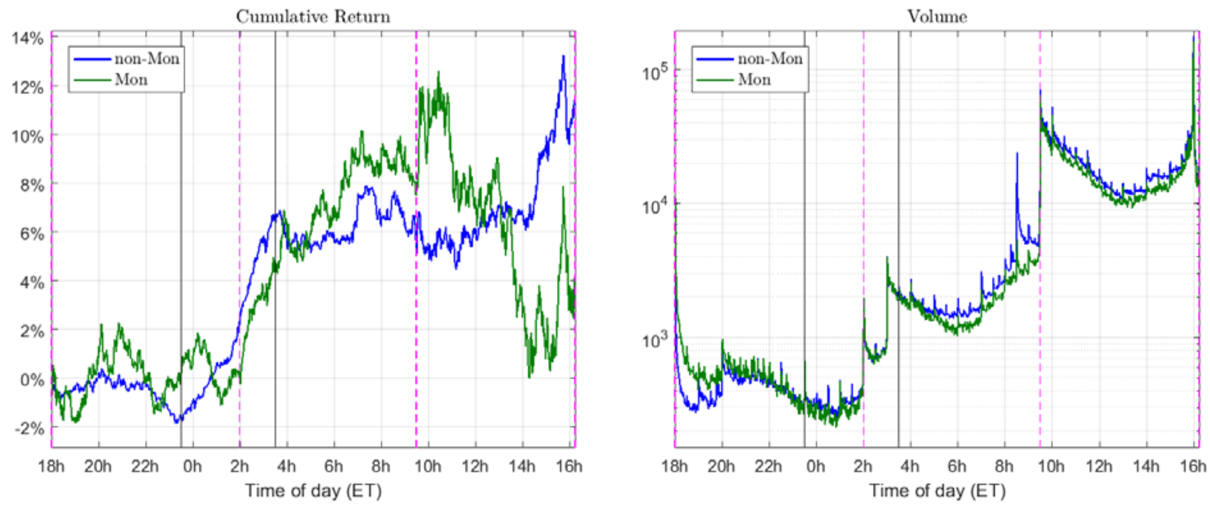


Figure IA.13
First and second part of the sample
This figure compares cumulative market return (left panel) and minute-by-minute trading volume (right panel) during a day for the first (pre-2011) and second (post-2011) part of the sample period. Trading volume increased markedly during post-2011, but 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 stock market open times.