Co-Movements of Index Options and Futures Quotes *

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Abstract

We re-examine the co-movements of index options and futures quotes first studied in Bakshi, Cao, and Chen (2000). We show that the frequency of quote co-movements that are inconsistent with standard option pricing models is significantly higher around option trades. We examine empirically two explanations for these co-movements. First, we show that in simulations the stochastic volatility model can generate approximately the right frequency of inconsistent co-movements when its parameters are chosen to match observed option prices. But even allowing for different regimes in trade and no-trade periods the model generates virtually the same frequency of inconsistent co-movements. Second, we examine the quote co-movements in event-time around trades and show that they are consistent with either traders picking off stale option quotes or with traders submitting aggressive limit orders. Our evidence suggest that inconsistent co-movements reflect both departures from the univariate diffusion model and market microstructure frictions.

Keywords: Options; Frictions; Market Microstructure; Stale Quotes; Market and Limit Orders
JEL codes: G13; G14; C33

1 Introduction

Recent studies document discrepancies between theoretical and actual co-movements of index options and futures. Bakshi, Cao and Chen (2000) report that co-movements of S&P 500 index options and futures often violate the predictions of standard option pricing models. Bossaerts and Hillion (2003) apply a new methodology that uses only local information on co-movements of index options and futures to price and hedge options on the DAX index. Their new methodology displays superior performance on simulated data (see Bossaerts and Hillion (1997)) but performs poorly on actual data, a finding that the authors attribute to frequent anomalous co-movements of the index options and futures. Both studies suggest that the observed co-movements may reflect a stochastic volatility process for the underlying asset. But they also suggest that even a richer process for the underlying asset may not completely rationalize the co-movements leaving market microstructure frictions as another possible explanation.[1] The existing evidence on the relative importance of such frictions is incomplete because variables that play a key role in most microstructure models, namely trades and signed orders, have not been considered.

We use a one-year sample of quotes and trades for European-style options and futures on the Financial Times Stock Exchange 100 stock index (FTSE 100) from the London International Financial Futures and Options Exchange (Liffe). Like Bakshi, Cao, and Chen (2000) we find that contrary to the predictions of standard option pricing models quote changes for call options and index futures frequently have opposite signs whereas quote changes for put options and index futures frequently have the same sign. We compute the frequency of such co-movements in periods with and without option trades and find large differences. For example, quote changes for call options and index futures are of opposite signs for approximately 30% of all one-minute intervals before and after an option trade but only for 7% of all one-minute intervals that are at least a minute away from a trade. Can these patterns in co-movements be reconciled with a stochastic volatility model?

[1]Bakshi et al. (2000) report that a stochastic volatility model fitted to their data can correctly predict 47% of the observations of a negative correlation between the call price and the price of the underlying asset leading them to conclude that "Thus, the SV [stochastic volatility model] explains about half of the type I violations, but it cannot be expected to be completely consistent with option data."

A stochastic volatility model can generate different predictions for trade and no-trade periods provided that trade and no-trade periods represent different regimes with innovations in the underlying stock index being more negatively correlated with innovations in volatility in trade periods. We use end-of-day option prices to estimate the model parameters for no-trade periods and all traded option prices to estimate the model parameters for trade periods. Using the two sets of parameter estimates we generate a series of predicted co-movements for the options and future quotes. The stochastic volatility model generates negative co-movements for call option and index futures for 10.8% of the observations using the no-trade period parameter values and for 12.0% of the observations using the trade period parameter values. The small difference implies that while the stochastic volatility model generates approximately the correct frequency of anomalous co-movements, it cannot rationalize the observed sharp increase in such violations around option trades.

An alternative explanation is that the observed patterns in co-movements are driven by market microstructure effects. But such explanations need to go beyond the predictions of a standard market maker framework. It is hard to reconcile the anomalous quote co-movements with rational quote updating by market makers. Why would market makers move their call option quotes down or their put option quotes up when the underlying stock index goes up?[2] Such quote co-movements are not consistent with frictions created by the minimum tick size, or the bid-ask spread, nor are they consistent with adverse selection or inventory based explanations. But the actual quote dynamics on both the Chicago Board Options Exchange (Cboe) and the Liffe reflect traders' limit order submissions which may be driven by different considerations than that of market makers' quote updates.

To gain a better understanding of the quote dynamics around trades we study the movements in the options and futures quotes for one-half hour intervals centered around the time of option trades. We compute the average mid-quote changes for the options and the futures both ten minutes before and after buyer- and seller-initiated option trades and identify two types of trader behavior that are associated with different patterns of co-movements.

[2]Bakshi, Cao, and Chen (2000) makes this point on page 551.

In the first case, a buyer-initiated trade in a call option occurs shortly after a trader submits an aggressive sell limit order that undercuts the current best ask quote by, on average, six ticks causing the call option mid-quote to temporarily decrease while the futures mid-quote is virtually unchanged. The quotes therefore move in opposite directions in 30% of the observations *both before and after* the trade as the option's mid-quote is temporarily pushed down before the trade and reverts back after the trade. In the second case, the change in the futures mid-quote over the 10 minutes before the buyer-initiated trade implies, on average, a two to three tick increase in the value of the call option but the call option's mid-quote is virtually unchanged and adjusts upwards only after the trade. The quotes therefore move in opposite directions for approximately 12% of the observations *before* and 30% of the observations *after* the trade because of the stale quote before and the delayed quote adjustment after the trade. We report analogous patterns for seller-initiated trades in call options and buyer- and seller-initiated trades in put options. In the first case traders seek liquidity by placing aggressive limit order that are likely to be executed quickly offering them a better price than a market order and in the second case traders pick off stale quotes.

We interpret our findings as evidence that the above market microstructure effects explain a significant fraction of the observed anomalous co-movements of index options and futures quotes around trades. It is plausible that aggressive limit orders that fail to execute and stale quotes that are not picked off explain some of the anomalous co-movements in intervals without trades. An implication is that in order to draw reliable inference from tests using high frequency data it is necessary to explicitly isolate market microstructure effects.

2 Description of the Market and the Sample

2.1 The Market

As of May 2000 all trading in financial contracts on Liffe takes place in an electronic limit order book system called Liffe Connect. In January 2002, Liffe became a part of Euronext to form a market called Euronext-Liffe. Euronext was formed by the merger of the Amsterdam, Brussels, and Paris stock and derivatives exchanges in September 2000. All derivatives trading on the different

Euronext satellite markets transferred to the Liffe Connect trading system in 2003.[3]

In the first half of 2001, the European-style FTSE 100 index option contract had an average monthly volume of 1.25 million contracts and an average monthly open interest of over 1.4 million contracts, and ranked fourth worldwide in trading volume among index option contract after the index option contracts on the S&P 100 and S&P 500 indices of the CBOE and on the DAX index of the Eurex.[4]

Orders are submitted electronically to the central limit order book. Incoming market orders are automatically matched with orders in the order book to produce trades. Orders are given priority according to price and orders at the same price are filled in a pro rata fashion according to order size.

Information on the best quotes and depths as well as quotes and depths away from the best quotes is distributed in real-time via Liffe Connect to the members' computer screens. In contrast, no information on the identity of members submitting orders is distributed. Trading is anonymous both before and after a trade.

Only exchange members can submit orders directly to Liffe Connect. There are no designated market makers with special quoting obligations or privileges in the FTSE 100 index options. In October 2002, there were 143 public order members. Public order members can trade on their own account or on behalf of their customers. There were also 60 non-public order members. Non-public order members can trade on their own account or on behalf of other members as brokers. Any member firm can use software, known as automated price injection models, that automatically generate order submissions or cancel outstanding orders.

2.2 The Sample

We obtained our sample from Liffe's market data services. It consists of time-series of all quotes and trades for all the European-style FTSE 100 index option contracts and the FTSE 100 index futures contracts. We also obtained the daily time-series of closing prices, open interest, and implied

[3]Other markets that use the Liffe Connect trading system are the Chicago Board of Trade and the Tokyo International Financial Futures Exchange.

[4]The rankings are based on volume figures provided by the Institute for Financial Markets (www.theifm.org). American-style options on the FTSE 100 index also exists on Liffe but they are less actively traded.

volatilities for all contracts.

Our sample period covers 242 trading days between August 1, 2001 and July 30, 2002. Six days were dropped from our sample because the quote and trade records are missing for more than three hours. For each contract, the sample consists of a time-series of the best bid and ask quotes with the corresponding total depths. A new observation is generated in the quote series for every change in either the best bid or ask quote or in the best bid or ask depth. All quotes are binding since trading is computerized.

Trading of the FTSE 100 index options and index futures is fully electronic and takes place in a common trading system which brings two advantages for empirical work. First, trades can be classified as buyer- or seller-initiated without error.[5] Second, option and futures quotes are synchronous, allowing us to determine the exact order and timing of quote changes around trades.

We use information on interest rates and dividend yields for computing the options' delta. We construct a proxy for the risk free interest rate using the overnight, one week, one month, three months and one year Sterling London Interbank Offered Rates (Libor), provided by Datastream. We construct a proxy for the interest rates for maturities other than the ones above via linear interpolation. We obtain daily dividend yields on the FTSE 100 index from Datastream. Our proxy for the dividend yield implicitly assumes market participants expect that the current dividend yield is an unbiased forecast of the dividend yield during the rest of the life of the option.

We drop all observations from our sample that violate one or more of the following criteria: (i) the bid or ask quote differs from the mid-quote by more than £30, (ii) the current bid or ask quote has not changed for more than 30 minutes, and (iii) the bid or the ask quote does not satisfy either the upper or lower bounds for rational call and put option prices. Applying the above criteria leaves us with 8,238,375 observations or approximately 95% of the original sample. Stale quotes and violations of the upper and lower bound for call and put option prices account for 80% of the excluded observations.

The first four rows of Table 1 report the mean and standard deviation for the bid-ask spread, the mid-quote, the depth at the best quotes, and the trade size for call options, put options, and

[5] Savickas and Wilson (2003) show, for a sample from CBOE's floor-based market, that trade classification algorithms that are often used for equity data correctly classify between 59 and 83% of option trades.

index futures. The mean spread is £8.7 for the call options and £8.6 for the put options. The minimum tick size of £0.5 is therefore not binding for a typical observation in our sample.[6] The mean depth and trade size are between 17 and 19 contracts for the call and put options. The mean trade size is close to the mean depth. The last two rows report the number of trades and quote updates.

We focus exclusively on the lead-month index futures contract because it is far more actively traded than the contracts with longer time to expiration. The mean spread is £1.5 or approximately 17% of the mean index option spread. The mean depth and trade size are approximately equal for the index futures and both are approximately one fifth of the corresponding means for the index options. The index futures are actively traded; there are approximately 30 index futures trades for every index option trade.

The total number of quote updates is approximately eight million for the index options compared to approximately six million for the lead-month index futures contract. But many different option series are traded on any given day. The number of index option contracts that are actively quoted varies across days, but at a minimum three strike prices with five different expiration dates are quoted for call and put options implying a total of 30 option series. With the index options' quote updates spread evenly over 30 different option series we have about 22 times as many quote updates for the index futures as for the typical option series.

Table 2 reports the mean of the quoted bid-ask spread, the option price, the quoted depth, the daily number of quote updates, the daily number of regular trades, and the trade size for regular trades for call and put options, sorted into three categories based on moneyness or time to expiration. The quoted bid-ask spread varies systematically with moneyness and time to expiration; in general at-the-money and out-of-the-money options and short time to expiration options have narrower spreads. The mean quoted depth varies between 15 and 24 contracts. Longer time to expiration and out-of-the-money contracts have higher quoted depths.

Quote updates outnumber trades for all moneyness and expiration categories. For example, for at-the-money calls there are 321 quote updates for every trade and for the shortest time to

[6] The FTSE 100 index options are quoted in index points. Each contract is valued at £10 per index point. The tick size is 0.5 index points or £5. We omit the index-point multiplier of ten in our empirical analysis.

expiration calls there are 192 quote updates for every trade. Quotes for at-the-money and short time to expiration options are updated more frequently than quotes for in-the-money options and longer time to expiration options.

3 Basic Properties of Option Prices

Bergman, Grundy, and Wiener (1996) show that when the underlying asset price follows a diffusion whose volatility depends only on time and the concurrent asset price, then a call option price is always increasing and convex in the underlying asset price. When volatility is stochastic, however, or the underlying asset price does not follow a diffusion, then the call price can be a decreasing or concave function of the stock price. One implication of their results is that the delta of a European-style option is bounded at any time $t < T$ before the option's expiration date T:

$$0 \leq \frac{\partial c(S,t)}{\partial S} \leq 1 \tag{1}$$

and

$$-1 \leq \frac{\partial p(S,t)}{\partial S} \leq 0, \tag{2}$$

where $c(\cdot)$ denotes the value of the call and $p(\cdot)$ denotes the value of the put option and S denotes the value of the underlying asset. Bergman et al. (1996) also show that as long as the option has some positive time value the inequalities in equations 1 and 2 are strict.

Following Bakshi, Cao, and Chen (2000) we use the mid-quotes of the options and the index futures as proxies for the value of the option and the the underlying index. We consider four types of violations of the inequalities in equations 1 and 2. Denote the time t mid-quote of the index futures by S_t and the time t mid-quotes of the call and put options by C_t and P_t. Denote the changes in the mid-quotes between $t - \tau < t$ and t by $dS = S_t - S_{t-\tau}$, $dC = C_t - C_{t-\tau}$, and $dP = P_t - P_{t-\tau}$. The four violations are then defined as follows where τ is small enough to ignore the effects of the option's time decay.

Definition 1 *The following four types of situations are violations of the basic properties in Equa-*

tions 1 and 2

$$
\begin{aligned}
Type\ I\ &: \begin{cases} \frac{dC}{dS} < 0 & and & dS \neq 0, \\ & or & \\ \frac{dP}{dS} > 0 & and & dS \neq 0. \end{cases} \\
Type\ II\ &: \begin{cases} dS \neq 0 & and & dC = 0, \\ & or & \\ dS \neq 0 & and & dP = 0. \end{cases} \\
Type\ III\ &: \begin{cases} dS = 0 & and & dC \neq 0, \\ & or & \\ dS = 0 & and & dP \neq 0. \end{cases} \\
Type\ IV\ &: \begin{cases} \frac{dC}{dS} > 1 & and & dS \neq 0, \\ & or & \\ \frac{dP}{dS} < -1 & and & dS \neq 0. \end{cases}
\end{aligned}
$$

Type I violations occur when the call option mid-quote moves in the opposite direction of the index futures mid-quote or when the put option mid-quote moves in the same direction as the index mid-quote. Type II violations occur when the option mid-quote is unchanged and the index futures mid-quote changes. Type III violations occur when the index futures mid-quote is unchanged and the option mid-quote changes. Type IV violations occur when the magnitude of change in the option mid-quote is greater than the magnitude of the change in the index futures mid-quote. As Bakshi et al. (2000) we will primarily focus on violations of type I and IV, which are more puzzling than violations of type II and III because they involve changes in *both* the option and the index futures mid-quotes.[7]

4 Empirical Results

4.1 Violation Rates: Trade versus No-Trade Intervals

Table 3 reports the mean rates of type I, II, III, and IV violations across all non-overlapping 30-minute intervals in our sample. The top panel reports mean violation rates for call options and the bottom panel reports the mean violation rates for put options. The top row of each panel reports the overall mean violation rates. The overall mean rates of type I and IV violations are of the same

[7] In our empirical analysis, we use the FTSE 100 index futures as a proxy for the underlying asset price. One advantage of the index futures price is that it is more likely to reflect all available information about the component stocks than the underlying index itself which may be based on individual stock quotes that are stale. Our proxy should not affect the frequency of violations I-III at all, but it may bias our result against finding evidence of violation IV. During our sample period, the interpolated interest rate r was always larger than the dividend yield δ on the FTSE 100 index. Therefore, the theoretical futures price $F_{T,t} = S_t \times exp(r - \delta)(T - t)$ is larger than the underlying index inflating the denominators in the inequalities for Type IV violations.

order of magnitude as the ones reported in Table 3 of Bakshi, Cao, and Chen (2000) suggesting that the violations may be a regularity of options data that holds across different markets, trading systems, and time periods. We find that type I violations occur in 8.9% of all call option intervals and in 9.2% of all put option intervals compared with 9.3% and 9.9% in their study. We find that type IV violations occur in 4.5% of all call option intervals and in 4.3% of all put option intervals compared with 7.3% and 9.8% in their study. Violations of type III occur in less than 2% of the intervals in both studies.

Violations of type II have a mean rate of 47.7% for call option intervals and 51.8% for the put option intervals which is much higher than in the sample of Bakshi et al. (2000) where the corresponding mean rates are 34.3% and 32.0%. A potential explanation is the difference in the relative tick size for the index futures in the two samples; in our sample the average value of the FTSE 100 index is around 5,000 and the tick size is 0.5 index points whereas the average value of the S&P 500 index was around 500 and the tick size was 0.1 index points in the period studied by Bakshi et al. (2000). The relative tick size in our sample is therefore approximately one-half of the one in their sample implying that we may observe more frequent changes in the index futures mid-quote, holding everything else equal, which would produce a higher rate of type II violations.

A smaller relative tick size may also explain why we find a lower rate of type IV violations because a finer tick size would tend to reduce any *stickiness* in the option quotes; a small quote change for the index futures may not cause the option quotes to change especially if the options are quoted in multiples of a relatively large tick size. In our sample it is also the case that the tick size is the same across the two markets implying that situations where a change in the index futures quote is smaller than the minimum tick size for the options cannot occur.

The second and third row of each panel report mean violation rates across all intervals in which no trades occur and all intervals in which at least one trade occurs. The differences in the rates of type I, II, and IV violations are large and a test of the null hypothesis that the violation rates are equal across trade and no-trade intervals strongly rejects the null in all cases. Type I and type IV violations occur on average twice as often in trade intervals as in no-trade intervals, while the Type II violations are more than five times as common in no-trade intervals as they are in trade intervals. The decrease in the rate of type II violations is not surprising because option quotes tend to change around the time of option trades. What is more surprising is that quote co-movements where option quotes move in either the 'wrong direction' or move by 'too much' are more common in periods when the options are traded.

We next examine finer time intervals to establish a closer link between the violations and trades. The bottom halves of each panel of Table 3 report the mean violation rates for 30 one-minute intervals centered around each option trade. We report four sets of mean violation rates: the overall violation rate across all 30 one-minute intervals for all trades, a mean violation rate for the one-minute intervals before a trade, a mean violation rate for the one-minute intervals after a trade, and a mean violation rate for all one-minute intervals at least one minute away from the trade.

Overall, Type I and IV violations are approximately four times as likely during the two one-minute intervals before and after a trade than during the other one-minute intervals. For example, in the one-minute interval before a put option trade the option mid-quote moves in the same direction as the index futures 26.3% of the time and moves in the opposite direction by more than the change in the index futures 15.6% of the time. The corresponding violation rates for the one-minute intervals away from the trade are 6.9% and 3.9%. The results show that there is a sharp increase in the anomalous quote co-movements right around the time of a trades that deserves a closer examination.

One possibility is that the correlation between trades and violations is indirect; perhaps the violation rates depend on the option characteristics such as moneyness or time to expiration which in turn are correlated with the trading activity. Table 4 and 5 report the mean rates of violation by type for different sub-groups formed based on the options' moneyness and time to expiration categories. Both tables show the non-overlapping 30-minute interval violation rates for nine different categories that consist of three moneyness and three time to expiration categories. The first number in each column is the violation rate for no-trade intervals, and the number in parentheses is the violation rate for trade intervals. While there are differences across categories, we find that for all moneyness and all time to expiration categories the violations of type I and IV occur more frequently in trade than in no-trade intervals for both call and put options. On average, across all nine categories type I and IV violations occur about three times as often in trade as in no-trade intervals.[8]

The bottom two rows in each panel report the mean of the absolute change in the mid-quote of the option and the index futures for each category and no-trade and trade intervals. For both call and put options and index futures the mean absolute mid-quote change is greater in trade intervals than in no-trade intervals across all categories. The difference is on average approximately 2.5 index points for the index futures and 5.5 index points for the index options.

Overall, type I and IV violations are strongly associated with trades and there is little evidence that the higher violation rates are systematically related to the options' moneyness or time to expiration. Mean absolute quote changes are greater in trade intervals than in no-trade intervals pointing to at least two possibilities. One possible explanation for this finding is that the underlying stock index follows a process that is characterized by stochastic volatility and a negative correlation between innovations in the underlying index and the volatility.

4.2 Can a Stochastic Volatility Model Explain the Violation Rates?

We design a simulation to explore to what extent a two-dimensional Markov diffusion model can help explain the different violation frequencies we observe for trade and no-trade intervals. We concentrate on Heston's (1993) stochastic volatility option pricing model. Heston suggest the following specification for the stock price and volatility process:

$$dS(t)/S(t) = rdt + \sqrt{\nu(t)}dW_S(t) \tag{3}$$

$$d\nu(t) = [\theta - \kappa\nu(t)]\,dt + \sigma\sqrt{\nu(t)}dW_\nu(t), \tag{4}$$

where dW_S and dW_ν are two Brownian motions with an instantaneous correlation coefficient ρ. A stochastic volatility model for option prices can explain some of the type I violations if the

[8] Dennis and Mayhew (2003) point out that price discreteness and rounding cause violations even when theoretically there should be none, i.e., when the underlying process is a one-dimensional diffusion. Their arguments apply in any setting including ours since prices are always discrete, but the differences across trade and no-trade periods that we find cannot be explained by price discreteness or rounding.

innovation in the stock price and the innovation in the volatility process are negatively correlated: a negative innovation in the stock price could be more than offset by a positive innovation to volatility, leading to a higher call option price, and causing dS and dC to be of opposite signs.

Following Bakshi, Cao, and Chen, we back out the stochastic volatility model's parameters from observed option prices. We define a parameter vector $\Phi = \{\kappa, \theta, \sigma, \rho, \nu\}$. We then minimize the sum of squared pricing errors:

$$\min_{\Phi} \sum_{n=1}^{N} \left(\hat{C}_n(t, \tau, K, S) - C_n(t, \tau, K, S) \right)^2, \tag{5}$$

where $\hat{C}_n$ is the observed option price for the n_{th} call, and C_n is its model price.

To capture the difference between trade and no-trade intervals, we use two different sub-samples. The first sub-sample consists of end-of-day mid-quotes for call options with a time-to-maturity of more than a week and a moneyness between 0.85, and 1.05. We assume that the end-of-day mid-quotes provide a good proxy for the behavior of the stock and volatility process during no-trade intervals.

The second sub-sample consists of all transaction prices for call options and the associated level of the index futures, with the same restrictions on moneyness and time-to-maturity. We assume that the traded call option prices capture the information available to traders around the trades, and provide a good proxy for the stock and volatility process during trade-intervals.

We fit the model each day of our sample period, and report an average of all daily parameter estimates in Table 6. The first column reports the average parameter estimates of the trades sample, the second column reports the parameter estimates of the end-of-day sample, and third column repeats the values of Bakshi, Cao, and Chen (2000). The estimate for ρ is -0.70 for trade periods and -0.53 implying that stock index and volatility innovations are more negatively correlated in trade periods.

In the next step, we use the above parameters to generate changes in S and ν, using the discretized versions of the continuous time stochastic processes for dS and $d\nu$:

$$S\left(t + \Delta_t\right) - S\left(t\right) = rS\left(t\right)\Delta_t + \sqrt{\nu(t)}S(t)\epsilon_1(t)\sqrt{\Delta_t} \tag{6}$$

$$\nu(t+\Delta_t) - \nu(t) = [\theta - \kappa\nu(t)]\,\Delta_t + \sigma\sqrt{\nu(t)}\epsilon_2(t)\sqrt{\Delta_t} \tag{7}$$

We set $\Delta_t = 1/(365\times 24\times 2)$ and generate 10,000 changes over 30-minute intervals. We calculate a change in the price of a typical call option of our sample ($S = 5,000$, $K = 5,125$, $r = 0.041$, $t = 0.22$) using Heston's formula and the simulated prices $S(t+\Delta_t)$ and $\nu(t+\Delta_t)$.

The bottom row of Table 6 reports the simulated frequencies of type I violations based on the two sets of parameter estimates for trade vs. no-trade periods and the parameter values used in Bakshi, Cao, and Chen (2000) (page 577). All three violation frequencies are relatively close to each other with the one based on no-trade periods being the lowest at 10.79%. For trade intervals this frequency increases to 12.01%. Thus, we cannot explain the large difference between the trade and no-trade intervals we document in Table 3. The violation frequency derived from the stochastic volatility model that is fitted to the trades sub-sample is only 1.2 percentage points or 11.3% higher than the frequency derived from the model fitted to the no-trades sub-sample. The 11.3% increase in the violation frequency is about one-tenth of the observed increase in violations for the 30-minute trade vs. no-trade intervals.

The violation rates of Table 6 are upper bounds for the explanatory potential of a stochastic volatility model. A generated type I violation by the stochastic volatility model does not necessarily coincide with an observed type I violation. There are two possible errors: the stochastic volatility model can generate a violation where there is none or it can miss an observed violation. For example, in Bakshi, Cao, and Chen (2000), the stochastic volatility model correctly predicts 47% of the observed violations of type I, which corresponds to 55% of the total type I predictions generated by the stochastic volatility model.

To determine whether similar results are obtained for our sample we randomly select one day from each month of our sample and divide the twelve days into sixteen one-half hour intervals. We fit a stochastic volatility model to all option prices within each interval by minimizing the sum of squared pricing errors. Using the estimated parameters we compute the change in the instantaneous volatility between two consecutive intervals and use it together with the observed change in the stock index futures to compute the predicted change in the options' mid-quotes between the consecutive intervals. We compute the observed mid-quote change using the mid-quotes prevailing at the beginning of each interval. For our sub-sample we observe 908 type I violations out of which 55% are predicted by the stochastic volatility model. There are also 422 observations for which the stochastic volatility model predicts a violation of type I but no violation is observed.

To summarize, we find that a stochastic volatility model can generate a frequency of violations of type I of approximately the right order of magnitude. But the difference in generated violation frequencies is small across trade and no-trade periods compared with the large difference observed in our sample. Furthermore, the stochastic volatility model when fitted to the data correctly predicts approximately half of the observed violations implying that approximately half of the violations are unexplained by the stochastic volatility model and there is a substantial fraction of false positives. So while a stochastic volatility model may accurately describe the cross-section of option prices and quotes on lower frequencies it seems to fail to capture many aspects of high frequency co-movements of the stock index and the option quotes. These findings suggest that there is considerable scope for alternative explanations of the observed quote co-movements.

4.3 Stale Quotes and Adverse Selection

Stale quotes may explain why violations of type I and IV are more frequent around trades than at other times. Stale quotes may attract traders because stale quotes typically imply a more favorable price for either buyers or sellers. If the index futures but not the option quotes reflect recent changes in the index we may observe a delayed quote revision for the options. A delayed quote revision may cause violations because the quote changes for the options and the index futures are asynchronous. For example, suppose the index futures quotes change by several ticks before the trade, while the option quotes remain constant. After the trade, the option quotes are revised to reflect the cumulative change in the index, which may cause the options quotes to change more than the index futures quotes after a trade. As a consequence we may observe both more frequent type I and type IV violations.

Adverse selection may also explain why violations of type I and IV are more frequent around trades than at other times. Suppose some traders have private information about the value of the index. Suppose the informed traders try to exploit their informational advantage in the index futures and index options market. If they trade on their information in both markets it is possible that we observe non-synchronous quote adjustments as trades in one market cause quotes in that market to reflect some of the informed traders' information that is not yet reflected in the quotes of the other market. When information is first reflected in index futures quotes we may observe that some option quotes are stale as discussed above. But if the new information is reflected in the option quotes first we may observe that the index futures respond to quote revisions in the options market. In such a situation, more frequent type I and IV violations may occur because we observe option quote revisions that go in the wrong direction or are too large when compared to contemporaneous index futures quote changes because they reflect new information. Subsequently we may observe the opposite situation when the index futures quotes change to reflect information that already is reflected in the option quotes.

Before examining whether stale quotes or adverse selection can explain the anomalous quote co-movements we address an even more basic question: Do the option trades convey new information? If option trades signal new information we may observe that the mid-quotes change after trades. The results on absolute mid-quote changes reported in Tables 4 and 5 suggest that quotes do change around the time of trades but do not tell us whether the quote changes are driven by the trades. We therefore test the following non-informative option trades hypothesis: The expected change in the option's mid-quote after a buyer- or a seller-initiated trade from the time of the trade to τ minutes after the trade is zero. Table 7 reports the mean changes in the option mid-quotes in the 5 minute period after buyer and seller initiated trades in the call and put options. Table 7 shows that the quotes are revised upwards after buyer-initiated trades and downwards after seller-initiated trades. In all cases the quote revisions are positive after buyer-initiated trades and negative after seller-initiated trades. The 'non-informative option trades' hypothesis is rejected at the 1%-level for all cases. Overall, the quote revisions are approximately 70% of the half-spread for buyer-initiated trades and 56% for seller-initiated trades implying that the realized spread earned by the liquidity provider is substantially smaller than the quoted spread; the liquidity providers earn 30% of the quoted half-spread on buyer-initiated and 44% of the quoted half-spread on seller-initiated trades.

But the results of Table 7 are consistent with both adverse selection and stale quotes. If quotes are stale at the time of the trade, then we should observe a positive quote revision following a buyer-initiated trade, and a negative quote revision following a seller-initiated trade. If there is adverse selection, then we should also observe a positive quote revision following a buyer-initiated trade, and a negative quote revision following a seller-initiated trade. In both cases the liquidity provider's realized spread is smaller than the quoted spread. The difference is that in the former case the quote revision follows a change in the index whereas in the latter case the trade itself may be followed by a change in the index.

We can use the index futures quotes to distinguish between the adverse selection and stale quote explanations. The option's delta multiplied by the change in the index futures mid-quote provides an implied change in the value of the option. The implied change is only an approximation since we ignore time decay, the option's gamma, and the difference between the index futures and the actual index. But for the short time intervals we are interested in we believe the approximation error is small enough to not affect the results. The descriptive statistics in Table 1 demonstrate that the index futures are more frequently traded than the options and that the index futures quotes are updated more frequently than the option quotes. It is therefore informative to ask whether the index futures changes after buyer- and seller-initiated trades in the options are consistent with adverse selection. We therefore test the following no adverse selection hypothesis: The expected change in the index futures mid-quote, multiplied by the option's delta, from the time of a trade t to τ minutes <u>after</u> the trade is non-positive for a buyer-initiated trades and non-negative for a seller-initiated trades. Table 8 reports the mean change in the index futures mid-quotes, multiplied by the options' delta, in the 5 minute period after call and put options trades. The top left panel reports the mean changes for buyer-initiated trades in call options and the top right panel reports the mean changes for seller-initiated trades in call options. The bottom panel reports the corresponding results for put options. The top row of each panel reports the overall results, and the next six rows report the results by three moneyness and three time to expiration categories. The number of observations and the average half-spread at the time of the trades is reported next to each mean change.

The average changes in the index futures mid-quote, multiplied by the option's delta, are close to zero in all cases. Overall, a small positive change is observed after buyer-initiated trades although only the change for call options is significantly different from zero. For seller-initiated trades the overall mean change is negative for call options and positive for put options, but in both cases we do not reject the 'no adverse selection' hypothesis. The results suggest that the changes in the option values implied by index futures quote changes after option trades are consistent with no adverse selection.

The results above points to stale quotes as the more plausible explanation for the option quote revisions reported in Table 7 following trades. If the option quotes are stale relative to the index futures quotes we would observe that the index futures quotes imply a change in the option value before a buyer- or seller-initiated trade. We therefore test the following no stale quotes hypothesis: The expected change in the index futures mid-quote, multiplied by the option's delta, from τ minutes before a trade to the time of a trade is non-positive for a buyer-initiated trade and non-negative for a seller-initiated trade. Table 9 reports the mean changes in the index mid-quotes, multiplied by the options' delta, from 5 minutes before buyer- and seller-initiated trades in the call and put options to the time of the trade.[9] In all cases the mean changes are positive for buyer-initiated trades and negative for seller-initiated trades. We reject the 'no stale quotes' hypothesis in all cases with the exception of two: The longest time to expiration buyer-initiated call category and the longest time to expiration seller-initiated put category. Overall, the average change is around 30% of the half-spread for buyer-initiated trades and 16% of the half-spread for seller-initiated trades suggesting that a substantial fraction of the option quote revisions reported in Table 7 are actually implied by index futures changes before the trades occur.

Overall, the results in Table 7 together with the results in Tables 8 and 9 are consistent with stale quotes in the sense that the index futures imply positive changes in the value of the options before the buyer-initiated trades and negative changes in the value of the options before seller-initiated trades.

[9]The number of observations and the mean spreads differ slightly between Table 9 and Table 8 because some observations lack valid quotes either before or after a trade.

Our results so far suggest stale quotes play a role but they do not imply the option quotes do not change before trades; the above results simply imply that the options quotes at the time of a trade are at least partly stale. From Table 9 we know that the index futures quotes change systematically before option trades. If the option quotes partly reflect the changes in the option values implied by the index futures quote we should observe positive option quote revisions before buyer-initiated trades and negative quote revisions before seller-initiated trades. We therefore test the following partial quote revision hypothesis: The expected change in the option's mid-quote from τ minutes <u>before</u> a trade to the time of a trade is non-positive for a buyer-initiated trade and non-negative for a seller-initiated trade. Table 10 reports the mean changes in the option mid-quotes from 5 minutes before a trade to the time of a trade for buyer- and seller-initiated trades in the call and put options. While the delta-weighted index futures changes reported in Table 9 imply that option mid-quotes—if not stale—increase before buyer-initiated trades and decrease before seller-initiated trades we find the exact opposite pattern for option mid-quotes. Before buyer-initiated trades the option mid-quote decreases and before seller-initiated trades the option mid-quote increases. Overall, the increase is approximately 36% of the quoted spread for buyer-initiated trades and the decrease is 41% of the quoted spread for seller-initiated trades. The 'partial quote revision' hypothesis is rejected in all cases with the exception of buyer-initiated trades in at- and in-the-money put options.

The last set of results suggests that stale or partly stale quotes cannot be the whole story. On average it appears that the mid-quotes change before trades, but that the mid-quote changes are in a direction opposite of the one implied by the index futures quotes. The results suggest that before the time of a trade the option quotes and the index futures quotes display anomalous co-movements. To gain a better understanding of the trading behavior around the option trades we examine in more detail the co-movements of the option and index futures quotes around buyer- and seller-initiated option trades.

4.4 Trader Behavior Around Trades

Figure 1 plots, in event time, the average changes in the mid-quotes of the index futures (thick solid line) and the index options (dotted line) around buyer-initiated trades in the call and put options. For each trade the series of mid-quotes are normalized so that changes are measured relative to the index futures mid-quote and the option mid-quote at the time of each trade. Note that unlike the results in Tables 8 and 9 we do not multiply the index futures quote change by the option's delta. Changes are plotted for every 10 second interval from 15 minutes before a trade to 15 minutes after a trade. The normalized bid quote for the index option is plotted with a dashed-dotted line and the normalized ask quote is plotted with a dashed line.[10]

Before a buyer-initiated trade the index mid-quote increases for call options and decreases for put options. The increase starts at about five minutes before the trade for calls and up to 15 minutes before the trade for puts although the most rapid change occurs in the last few minutes before the trade. If the value of the call option is increasing and the value of the put option is decreasing in the underlying index, the observed movements are consistent with the trade resulting from a stale limit order being picked off by a market order.

Figure 2 plots the corresponding picture for seller-initiated trades. The pattern of the index mid-quote changes is the reverse for seller-initiated trades. The index return is negative over our sample period which may explain why the average index decrease is larger in absolute value.

The changes in the index futures mid-quote are consistent with the 5-minute changes reported in Table 9. The relatively small changes in the index futures mid-quote after a trade are consistent with the results in Table 8.

The increase in the option mid-quote after a buyer-initiated trade is at least partly due to the ask quote shifting up; on average the bid quote has already adjusted before the buyer-initiated trade. Similarly for seller-initiated trades the decrease in the mid-quote after a trade is partly driven by a decrease in the bid quote. The above evidence is consistent with the quotes being stale at the time of the trade.

[10] Unconditionally, the index futures mid-quotes are slightly positively autocorrelated for very short horizons. The first-order autocorrelation coefficient for minute-by-minute mid-quote returns is 0.08 and we reject the null of zero autocorrelation at the 1% level or better. Higher-order autocorrelations are close to zero.

But the discrete negative jump in the ask quote within the last minute before a buyer-initiated trade and the discrete positive jump in the bid quote before a seller-initiated trade are not consistent with stale quotes. The plots show why the 'partial quote revision' hypothesis was rejected. In the case of stale quotes we would expect that the passive side of the trade—the ask quote for buyer-initiated trades and the bid quote for seller-initiated trades—would be a quote that has been in effect for some time and therefore does not reflect all available information including the recent changes in the index futures quote. But the plots show that instead the ask quote for buyer-initiated trades and the bid quote for seller-initiated trades are submitted shortly before the trade so the quotes are not stale.

The discrete negative jump in the ask quote before a buyer-initiated trade and the discrete positive jump in the bid quote before a seller-initiated trade are puzzling. They contradict the stale quote explanation because the quotes involved in the trades are evidently not stale. Yet, the jumps are hard to reconcile with standard quote updating since they are in a direction opposite to that implied by the change in the underlying index. In principle, such updates could reflect innovations in expected volatility that are negatively correlated with innovations in the underlying asset, but that seems doubtful given the symmetric update patterns across calls and puts. In the next section we examine the quote co-movements more closely by splitting the trades into aggressive quotes that involve a discrete jump and stale quotes that involve no quote change prior to a trade.

4.4.1 Aggressive Quotes versus Stale Quotes

To potentially distinguish between different trading behaviors we separate our sample of trades into three categories: The first category contains all buyer-initiated trades for which the option's ask quote was not updated during the 30 seconds prior to the trade. The second category contains all seller-initiated trades for which the option's bid quote was not updated during the 30 seconds prior to the trade, and the third category contains all remaining options.[11] We refer to the first two categories as the stale quote categories. The third category, which we refer to as the aggressive quote category, contains approximately 35% of all call option trades, and 37% of all put option

[11] The choice of thirty seconds is arbitrary. We have also used 60 seconds and 45 seconds, with virtually the same results.

trades.

Figures 3 and 4 plot the mean of the normalized mid-quotes series for the index futures and the mean of the normalized ask, bid, and mid-quotes for the options. Each option quote series is normalized by subtracting the option mid-quote at the time of the trade, and each index futures mid-quote series is normalized by subtracting the index future mid-quote value at the time of the trade.

The index movements prior to the trade and the behavior of the ask and bid quote series around the trade are different for the stale quote and aggressive quote categories. The top sub-plots of Figure 3 show the series for seller-initiated trades for which the option's mid-quote changed in the 30 seconds prior to the trade. The index movements before and after the trade exhibit a slight downward trend but there are no drastic changes over the 30-minute window. The ask quote series is relatively smooth, but the bid quote series contains—on average—a positive jump of almost 6 ticks at the time of the trade. Compared to the jump of Figure 2, it is more than 50% larger. Note that the bid reverts to its level before the trade shortly after the trade; consistent with that, there does not appear to be a systematic revision in the option's mid-quote after the trade ignoring the jump.

The bottom sub-plots of Figure 3 show that on average the index decreases by about 12 ticks before seller-initiated trades in the calls and increases by about 10 ticks before seller-initiated trades in the puts. The directions of the quote changes for both call and put options are consistent with stale quotes being picked off. Consistent with a stale quotes explanation, the bid and mid-quotes are revised downward post trade. Figure 4 shows the corresponding figures for buyer-initiated trades. Figure 4 demonstrates that the patterns described for seller-initiated trades also hold for buyer-initiated trades.

By splitting the sample into the two groups, we demonstrate that there are two scenarios for trades. In the first scenario, stale quotes are picked off. In the second scenario, traders post aggressive bid and ask quotes right before a trade. In the next section we revisit the violations and examine whether the violation rates differ for trades associated with aggressive and stale quotes.

4.4.2 Frequency of Violations Revisited

Table 11 reports the violation frequencies of one-minute intervals centered around trades, similar to the lower half of the call and put panel of Table 3. We use the three categories obtained by the separation of trades into trades most likely caused by stale quotes and trades caused by liquidity seeking behavior, either through an aggressive ask or bid quote. For each option trade, we again construct 30 one-minute intervals centered around the trade (which are potentially overlapping for different trades). We aggregate the intervals into three groups, the one-minute intervals immediately before the trade, immediately after the trade, and all other one-minute intervals, and document average violation frequencies for all such intervals.

Table 3 demonstrates that there are different violation patterns for quotes in the two minutes immediately surrounding the trades and the other 28 one-minute intervals, but that there is no substantial difference in the one-minute pre- and post-trade. Table 11 shows that there is a considerable difference in violations within the two one-minute intervals surrounding the trade once we separate them into trades against stale quotes and trade against aggressive quotes. Violations I and IV are much less likely in the minute prior to the trade for both call and put options when quotes are stale, but in the minute after the trades, the quotes often generate such violations consistent with the quotes being adjusted to the index changes plotted in Figures 3 and 4.

The last six rows of the call and put panel of Table 11 shows that around trades preceded by aggressive quotes violations of type I and IV occur both before and after a trade with approximately the same frequencies. This makes sense because the aggressive quotes appear to be submitted independently of index movements (see the upper subplots of Figures 3 and 4), and they undercut the current ask or bid by multiple tick sizes. After the trade, the ask or bid revert to their pre-trade level, and if the index movement surrounding the trade is small, or moving in the opposite direction, we observe a type IV or type I violation. Interestingly, the differences in violation rates for the three categories is small for the other intervals surrounding the trade.

5 Conclusions

We re-examine the role of market microstructure effects in explaining the anomalous co-movements of index options and futures quotes first reported by Bakshi, Cao, and Chen (2000). We show that the frequency of co-movements that are inconsistent with the predictions of standard option pricing models is much higher in periods around option trades and that the patterns of co-movements around option trades are consistent with specific order submission strategies.

We show that in our sample a stochastic volatility model can explain approximately half of the observed negative co-movements for call options but it does not explain the higher frequency of such co-movements around option trades. Overall our results imply that market microstructure effects play a bigger role in explaining high frequency co-movements of index options and index futures quotes.

One promising direction for future research is to consider model frameworks that combine some of the key elements of traders' order submission behavior with some plausible pricing model. Such frameworks may, for example, be useful in refining the types of high-frequency pricing and hedging approaches used by Bossaerts and Hillion (2003). Such frameworks may also allow us to draw useful inference about the motives for option trading from high frequency options data.

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Table 1: **Descriptive Statistics**

Variable	Call Options Mean	Call Options Std.Dev.	Put Options Mean	Put Options Std.Dev.	Index Futures Mean	Index Futures Std.Dev.
Quoted bid-ask spread [£]	8.7	5.9	8.6	5.8	1.5	1.0
Mid-quote	126.9	105.3	128.8	111.7	5003.1	386.1
Quoted depth	17.3	13.6	18.8	14.5	3.1	3.9
Trade size	17.0	71.3	19.7	60.4	3.4	7.2
Number of trades	29,456		36,227		2,433,108	
Number of quote updates	4,135,543		4,103,832		5,953,337	

The first four rows of the table report the mean and the standard deviation for the quoted bid-ask spread, the mid-quote, the quoted depth, and the trade size for index call options, put options, and index futures. The bottom two rows report the total number of trades and quote updates. A quote update is defined as a change in either the best bid or ask quote or in the best bid or ask depth. The depth and the trade size are measured in number of contracts. The depth is the average of the bid depth and the ask depth at the best quotes.

Table 2: **Descriptive Statistics by the Options' Moneyness and Time to Expiration**

	Bid-ask spread	Mid-quote	Quoted depth	No. of quote updates	No. of Trades	Trade size
			Call options			
Moneyness						
out-of-the-money	8.9	81.4	19.3	10,074.2	73.1	20.9
at-the-money	8.4	140.1	16.2	14,940.1	46.6	10.8
in-the-money	12.0	373.7	14.9	1,353.2	5.7	19.5
Time to Expiration						
less than 2 months	7.4	103.0	16.4	19,031.0	99.3	15.1
2 to 6 months	10.2	171.6	18.8	5,455.2	19.6	20.6
more than 6 months	18.6	238.4	22.6	1,764.1	6.1	40.5
			Put options			
Moneyness						
out-of-the-money	8.4	75.2	20.8	10,351.6	87.2	24.7
at-the-money	8.3	139.1	17.6	14,017.7	53.6	13.6
in-the-money	12.0	377.3	16.8	2,040.3	13.0	9.6
Time to Expiration						
less than 2 months	7.4	106.1	18.0	19,325.3	117.6	19.7
2 to 6 months	9.7	177.1	20.1	5,333.1	28.1	19.6
more than 6 months	18.0	228.6	23.6	1,588.3	8.2	20.1

The table reports, for call and put options, the means of six variables for the call and the put options for two sub-samples based on the options' moneyness and time to expiration. A call option's moneyness depends on the ratio of its strike price to the underlying; if the ratio is less than 0.97 the call is out-of-the-money; if the ratio is between 0.97 and 1.03 it is at-the-money; and if the ratio is above 1.03 it is in-the-money. Put options are classified similarly using the underlying divided by the strike price. Means for the following six variables are reported: the quoted bid-ask spread, the mid-quote, the quoted depth, the daily number of quote updates, the daily number of trades, and the trade size. A Wilcoxon test rejects the null hypothesis of equal median values for each variable across the moneyness and time to expiration categories for all cases with p-values less than 0.001.

Table 3: **Mean Violation Rates**

Call Options	N	I	II	III	IV	Total
		Type [%]				
30-minute non-overlapping intervals						
All	176,308	8.9	47.7	1.3	4.5	62.4
Only no-trade	161,433	8.2	51.3	1.2	4.2	64.9
Only trade	14,875	16.6	9.3	2.4	8.4	36.7
Thirty 1-minute intervals centered around each trade						
All	725,064	8.4	55.9	2.4	4.7	71.4
Minute before trade	25,449	27.5	21.1	6.2	14.4	69.2
Minute after trade	26,383	32.7	15.1	6.8	17.7	72.3
All other 28 intervals	673,232	6.7	58.8	2.1	3.8	71.4

Put Options	N	I	II	III	IV	Total
30-minute non-overlapping intervals						
All	236,545	9.2	51.8	1.2	4.3	66.5
Only no-trade	219,863	8.5	55.0	1.1	3.9	68.5
Only trade	16,682	17.9	9.0	2.7	10.3	39.9
Thirty 1-minute intervals centered around each trade						
All	837,449	8.5	59.0	2.1	4.9	74.5
Minute before trade	29,870	26.3	22.7	5.1	15.6	69.7
Minute after trade	31,329	32.2	17.4	6.4	18.2	74.2
All other 28 intervals	776,250	6.9	62.1	1.8	3.9	74.7

The table reports the mean rates of type I, type II, type III, and type IV violations. The top panel reports mean rates for call options and the bottom panel reports mean rates for put options. In each panel, the first three rows report results using non-overlapping 30-minute intervals and the next four rows report results using thirty 1-minute intervals, possibly overlapping, centered around trades. In the latter case the intervals are split into fifteen 1-minute sub-intervals before and fifteen 1-minute sub-intervals after a trade. The first row reports the mean rate for all intervals (per 30 minutes), the second row reports the mean rate for all intervals in which no trade occurred, and the third row reports the mean rate for all intervals in which a trade occurred. The fourth row reports the mean rate for all intervals (per minute), the fifth and sixth row reports the mean rate for the middle two intervals (the minute before and after a trade), and the seventh row reports the mean rate for all other 28 intervals around a trade. The different types of violations are presented in Definition 1.

Table 4: **Violation Rates and Moneyness and Time to Expiration—Call Options**

Monyeness		Time to Expiration less than 2		2-6 months		more than 6	
out-of-the-money							
	Violations						
	I	11.1	(18.7)	8.6	(22.6)	6.8	(22.6)
	II	50.4	(13.5)	55.5	(11.8)	50.2	(13.3)
	III	1.3	(2.6)	1.1	(2.5)	1.7	(2.4)
	IV	2.4	(4.1)	2.8	(8.8)	3.1	(8.1)
	Total	65.2	(38.9)	68.0	(45.7)	61.8	(46.4)
	Mean of absolute mid-quote change						
	Option	1.1	(2.6)	1.3	(3.4)	1.4	(3.6)
	Index Futures	9.5	(12.3)	9.3	(10.9)	8.0	(10.9)
at-the-money							
	Violations						
	I	7.9	(11.9)	7.5	(14.4)	6.4	(20.7)
	II	32.1	(4.4)	44.4	(6.0)	51.3	(4.6)
	III	1.5	(2.1)	1.3	(2.7)	1.5	(3.4)
	IV	6.7	(9.8)	6.8	(15.3)	6.8	(17.2)
	Total	48.2	(28.2)	60.0	(38.4)	65.9	(45.9)
	Mean of absolute mid-quote change						
	Option	3.0	(4.9)	2.8	(5.8)	2.3	(7.7)
	Index Futures	8.6	(10.2)	8.7	(10.1)	7.8	(8.7)
in-the-money							
	Violations						
	I	4.3	(20.3)	3.5	(23.0)	3.1	(*)
	II	80.2	(5.9)	81.1	(8.2)	76.0	(*)
	III	0.5	(1.7)	0.3	(1.6)	0.8	(*)
	IV	4.3	(31.8)	3.6	(27.9)	3.9	(*)
	Total	89.3	(59.7)	88.5	(60.7)	83.8	(*)
	Mean of absolute mid-quote change						
	Option	1.7	(14.5)	1.3	(10.0)	1.0	(*)
	Index Futures	9.1	(13.6)	9.3	(10.3)	8.0	(*)

* Less than 25 observations and thus omitted.

The table reports mean rate of type I, type II, type III, type IV and the total rate violations for call options by moneyness and time to expiration categories, each as a percentage of total numbers of 30-minutes intervals. A call option's moneyness depends on the ratio of its strike price to the underlying; if the ratio is less than 0.97 the call is out-of-the-money; if the ratio is between 0.97 and 1.03 it is at-the-money; and if the ratio is above 1.03 it is in-the-money. The mean rate for intervals with a trade are reported in parenthesis next to the mean rates for intervals with no trade. The mean absolute mid-quote change for the call options and the index futures are reported below the total violation rates. The mean absolute mid-quote change for intervals with a trade is reported in parenthesis next to the mean for no-trade intervals. The mid-quote changes are measured in pounds and for the index futures the nearest-to-maturity index futures are used.

Table 5: **Violation Rates and Moneyness and Time to Expiration—Put Options**

		Time to Expiration					
Monyeness		less than 2		2-6 months		more than 6	
out-of-the-money							
	Violations						
	I	10.6	(20.2)	8.6	(24.0)	8.3	(24.9)
	II	54.5	(12.5)	60.0	(12.8)	55.4	(11.4)
	III	1.0	(2.1)	1.1	(3.1)	1.4	(1.3)
	IV	2.3	(5.4)	2.6	(7.6)	3.0	(9.1)
	Total	67.4	(40.2)	72.3	(47.5)	68.1	(46.7)
	Mean of absolute mid-quote change						
	Option	0.9	(2.7)	1.1	(3.6)	1.1	(3.7)
	Index Futures	8.9	(11.6)	8.9	(11.1)	8.2	(11.1)
at-the-money							
	Violations						
	I	8.6	(11.6)	8.1	(15.8)	7.9	(18.6)
	II	32.0	(4.1)	43.5	(5.2)	51.4	(6.8)
	III	1.5	(2.3)	1.1	(3.4)	1.4	(3.4)
	IV	7.0	(10.8)	6.6	(14.3)	6.1	(25.4)
	Total	49.1	(28.8)	59.3	(38.7)	66.8	(54.2)
	Mean of absolute mid-quote change						
	Option	3.1	(6.1)	2.8	(6.7)	2.3	(7.5)
	Index Futures	8.6	(11.7)	9.0	(11.5)	8.4	(11.0)
in-the-money							
	Violations						
	I	4.3	(22.9)	3.7	(22.2)	5.2	(25.0)
	II	80.0	(7.5)	78.1	(11.1)	71.8	(3.1)
	III	0.6	(6.3)	0.8	(8.1)	1.1	(12.5)
	IV	5.1	(30.4)	4.5	(26.2)	5.4	(28.1)
	Total	90.0	(67.1)	87.1	(67.6)	83.5	(68.7)
	Mean of absolute mid-quote change						
	Option	2.0	(17.6)	1.8	(17.7)	2.0	(9.1)
	Index Futures	10.4	(14.1)	10.5	(13.8)	9.3	(6.4)

The table reports mean rate of type I, type II, type III, type IV and the total rate violations for put options by moneyness and time to expiration categories, each as a percentage of total numbers of 30-minutes intervals. A put option's moneyness depends on the ratio of the underlying to its strike price to; if the ratio is less than 0.97 the call is out-of-the-money; if the ratio is between 0.97 and 1.03 it is at-the-money; and if the ratio is above 1.03 it is in-the-money. The mean rate for intervals with a trade are reported in parenthesis next to the mean rates for intervals with no trade. The mean absolute mid-quote change for the call options and the index futures are reported below the total violation rates. The mean absolute mid-quote change for intervals with a trade is reported in parenthesis next to the mean for no-trade intervals. The mid-quote changes are measured in pounds and for the index futures the nearest-to-maturity index futures are used.

Table 6: **Stochastic Volatility Model Parameters and Simulated Violation Frequencies**

The first six rows of the table report three different sets of daily average parameter estimates for a stochastic volatility model. The first column labeled 'Trades' reports the parameters using transaction prices for all options with that with moneyness between 0.85 and 1.15 and time-to-maturity of more than one week. The second column labeled 'No-Trade' reports the daily average parameter estimates using the end-of-day mid-quotes for options with moneyness between 0.85 and 1.15 and time-to-maturity of more than one week. The third column reports the corresponding parameter values of Bakshi, Cao, and Chen (2000). The bottom row reports the simulated frequencies of violation of Type I corresponding to each set of parameters values.

Parameter	Trade	No-Trade	BCC (2000)
κ	2.455	4.190	2.180
θ	0.103	0.029	0.080
σ	0.663	0.463	0.530
ρ	-0.697	-0.527	-0.700
ν	0.038	0.031	0.023
$\sqrt{\nu}$	0.195	0.176	0.150
Type I Violations	12.01%	10.79%	12.79%

Table 7: **Option Mid-quote Changes 5 Minutes After Option Trades**

	Buyer initiated			Seller initiated		
	N	Spread	Change	N	Spread	Change
			Call options			
All	13,795	2.15	1.60**	14,705	2.31	-1.23**
Moneyness						
out-of-the-money	8,045	1.98	1.41**	7,878	2.10	-1.07**
at-the-money	5,153	2.21	1.69**	6,170	2.46	-1.30**
in-the-money	597	3.97	3.37**	657	3.49	-2.54**
Expiration						
less than 2 months	11,128	1.99	1.57**	11,787	2.20	-1.17**
2-6 months	2,145	2.79	1.75**	2,291	2.67	-1.35**
more than 6 months	522	2.93	1.67**	627	3.06	-1.85**
			Put options			
All	17,040	2.40	1.57**	17,888	2.45	-1.44**
Moneyness						
out-of-the-money	9,641	1.93	1.29**	9,698	1.91	-1.07**
at-the-money	5,937	2.67	1.85**	6,419	2.73	-1.70**
in-the-money	1,462	4.37	2.31**	1,771	4.36	-2.46**
Expiration						
less than 2 months	12,960	2.24	1.58**	14,065	2.31	-1.36**
2-6 months	3,238	2.89	1.52**	3,083	2.98	-1.77**
more than 6 months	842	3.01	1.72**	740	2.77	-1.46**

The table reports for all option trades the mean change in the option's mid-quote from the time of a trade to 5 minutes after the trade. The top panel reports the means for call options and the bottom panel reports the means for put options. The means for buyer initiated trades are reported on the left and the means for seller initiated trades on the right. The number of observations and the mean quoted half-spread at the time of a trade are reported next to the mean changes for each category. A ** indicates that the change is statistically significant at the 1% level or better.

Table 8: **Index Mid-quote Changes 5 Minutes After Option Trades**

	Buyer initiated			Seller initiated		
	N	Spread	Delta∗ Change	N	Spread	Delta∗ Change
			Call options			
All	14,190	2.01	0.05**	15,110	2.25	-0.04
Moneyness						
out-of-the-money	8,458	1.86	0.01	8,315	2.15	-0.06
at-the-money	5,163	2.07	-0.15**	6,178	2.30	-0.06
in-the-money	569	3.62	0.16	617	3.17	0.27
Expiration						
less than 2 months	11,497	1.84	0.06**	12,113	2.11	0.04
2-6 months	2,186	2.66	0.02	2,343	2.67	0.00
more than 6 months	507	2.90	0.13	654	3.40	0.22**
			Put options			
All	17,700	2.14	0.08	18,553	2.23	0.01
Moneyness						
out-of-the-money	10,401	1.87	0.03	10,452	1.85	0.02
at-the-money	5,939	2.28	0.08	6,458	2.41	0.04
in-the-money	1,360	3.57	0.39	1,643	3.88	-0.06
Expiration						
less than 2 months	13,347	1.99	0.09	14,669	2.08	0.03
2-6 months	3,480	2.59	0.01	3,110	2.77	0.04
more than 6 months	873	2.59	0.09*	774	2.84	0.06

The table reports for all option trades the mean changes in the index futures mid-quote from the time of a trade to 5 minutes after the trade multiplied by the option's delta. The top panel reports the means for call options and the bottom panel reports the means for put options. The means for buyer initiated trades are reported on the left and the means for seller initiated trades on the right. The number of observations and the mean quoted half-spread at the time of a trade are reported next to the mean changes for each category. A * (**) indicates that the change is statistically significant at the 5% (1%) level or better.

Table 9: **Index Mid-quote Changes 5 Minutes Before Option Trades**

	Buyer initiated			Seller initiated		
	N	Spread	Delta∗ Change	N	Spread	Delta∗ Change
			Call options			
All	13,910	1.98	0.51**	14,740	2.23	-0.28**
Moneyness						
out-of-the-money	8,305	1.85	0.24**	8,135	2.14	-0.19**
at-the-money	5,043	2.04	0.75**	5,996	2.27	-0.34**
in-the-money	562	3.58	2.29**	609	3.15	-1.06**
Expiration						
less than 2 months	11,248	1.82	0.59**	11,795	2.09	-0.28**
2-6 months	2,162	2.64	0.26**	2,296	2.65	-0.30**
more than 6 months	500	2.86	0.03	649	3.41	-0.31**
			Put options			
All	17,444	2.13	0.77**	18,284	2.22	-0.45**
Moneyness						
out-of-the-money	10,273	1.87	0.25**	10,327	1.85	-0.13**
at-the-money	5,825	2.26	1.42**	6,329	2.40	-0.81**
in-the-money	1,346	3.57	1.98**	1,628	3.88	-1.04**
Expiration						
less than 2 months	13,125	1.98	0.84**	14,427	2.07	-0.48**
2-6 months	3,452	2.58	0.55**	3,085	2.77	-0.33**
more than 6 months	867	2.59	0.55**	772	2.84	-0.20

The table reports for all option trades the mean changes in the index futures mid-quote from 5 minutes before a trade to the time of a trade multiplied by the option's delta. The top panel reports the means for call options and the bottom panel reports the means for put options. The means for buyer initiated trades are reported on the left and the means for seller initiated trades on the right. The number of observations and the mean quoted half-spread at the time of a trade are reported next to the mean changes for each category. A ** indicates that the change is statistically significant at the 1% level or better.

Table 10: **Option Mid-quote Changes 5 Minutes Before Option Trades**

	Buyer initiated			Seller initiated		
	N	Spread	Change	N	Spread	Change
			Call options			
All	10,944	1.97	-0.94**	11,540	2.18	0.90**
Moneyness						
out-of-the-money	6,230	1.83	-1.03**	5,969	2.00	0.82**
at-the-money	4,456	2.05	-0.89**	5,313	2.32	0.89**
in-the-money	258	4.01	0.57	258	3.41	3.03**
Expiration						
less than 2 months	9,434	1.86	-0.83**	9,855	2.11	0.85**
2-6 months	1,308	2.59	-1.57**	1,423	2.54	1.12**
more than 6 months	202	2.77	-2.04**	262	2.98	1.55**
			Put options			
All	12,409	2.23	-0.55**	13,016	2.23	0.93**
Moneyness						
out-of-the-money	6,754	1.82	-0.99**	6,877	1.77	0.86**
at-the-money	5,097	2.52	-0.09	5,449	2.54	0.92**
in-the-money	558	4.43	0.66*	690	4.28	1.86**
Expiration						
less than 2 months	10,178	2.13	-0.45**	11,000	2.14	0.84**
2-6 months	1,833	2.70	-0.99**	1,711	2.69	1.43**
more than 6 months	398	2.49	-1.00**	305	2.71	1.67**

The table reports for all option trades the mean changes in the option's mid-quote from 5 minutes before a trade to the time of a trade. The top panel reports the means for call options and the bottom panel reports the means for put options. The means for buyer initiated trades are reported on the left and the means for seller initiated trades on the right. The number of observations and the mean quoted half-spread at the time of a trade are reported next to the mean changes for each category. A ** indicates that the change is statistically significant at the 1% level or better.

Table 11: **Violation Rates for Trades Against Stale and Aggressive Quotes**

		Violations by Type [%]				
	N	I	II	III	IV	Total
Call Options						
All trades						
Minute before trade	25,449	27.5	21.1	6.2	14.4	69.2
Minute after trade	26,383	32.7	15.1	6.8	17.7	72.3
All other 28 intervals	673,232	6.7	58.8	2.1	3.8	71.4
Trades against stale quotes						
Minute before trade	8,769	12.4	52.4	2.5	3.9	71.2
Minute after trade	8,914	30.2	22.0	6.0	16.5	74.7
All other 28 intervals	230,048	6.8	61.1	2.0	3.4	73.3
Buyer-initiated trades against aggressive quotes						
Minute before trade	7,796	36.8	4.4	7.5	20.3	69.0
Minute after trade	8,156	35.2	10.8	6.9	19.0	71.9
All other 28 intervals	207,188	6.7	58.7	2.1	3.8	71.3
Seller-initiated trades against aggressive quotes						
Minute before trade	8,884	34.3	5.0	8.9	19.7	67.9
Minute after trade	9,313	33.0	12.2	7.5	17.5	70.2
All other 28 intervals	235,996	6.7	56.5	2.3	4.1	69.6
Put Options						
All trades						
Minute before trade	29,870	26.3	22.7	5.1	15.6	69.7
Minute after trade	31,329	32.2	17.4	6.4	18.2	74.2
All other 28 intervals	776,250	6.9	62.1	1.8	3.9	74.7
Trades against stale quotes						
Minute before trade	11,170	12.9	52.0	2.1	4.5	71.5
Minute after trade	11,450	29.7	25.2	5.8	16.2	76.9
All other 28 intervals	287,264	7.0	63.2	1.8	3.7	75.7
Buyer-initiated trades against aggressive quotes						
Minute before trade	8,971	33.9	5.1	6.6	22.8	68.4
Minute after trade	9,550	34.1	13.0	6.2	20.7	74.0
All other 28 intervals	234,774	6.7	61.8	1.7	4.0	74.2
Seller-initiated trades against aggressive quotes						
Minute before trade	9,729	34.7	5.2	7.1	21.7	68.7
Minute after trade	10,329	33.3	12.7	7.2	18.2	71.4
All other 28 intervals	254,212	6.8	61.1	2.0	3.9	73.8

The table reports the mean rates of type I, type II, type III, and type IV violations for buyer- and seller-initiated trades in call and put options split into three groups depending on whether there was a change in the best ask quote (buyer initiated) or bid quote (seller initiated) or no change in either within the last 30 seconds before the trade. The top panel reports mean rates for call options and the bottom panel reports mean rates for put options. The table reports results using thirty 1-minute intervals, possibly overlapping, centered around trades. The intervals are split into fifteen 1-minute sub-intervals before and fifteen 1-minute sub-intervals after a trade. The first three rows report the mean rate for all trades, the next three rows report the mean rate for all trades that were classified as potentially stale, the following three rows report results for buyer-initiated trades in which there was a change in the best ask and the last three rows show results for trades in which there was a change in the best bid in the thirty seconds prior to a trade. Within each block, the first row shows average values for the minute prior to the trade, the middle row shows average for the minute after the trade, and the last row shows averages for all other 1-minute intervals.

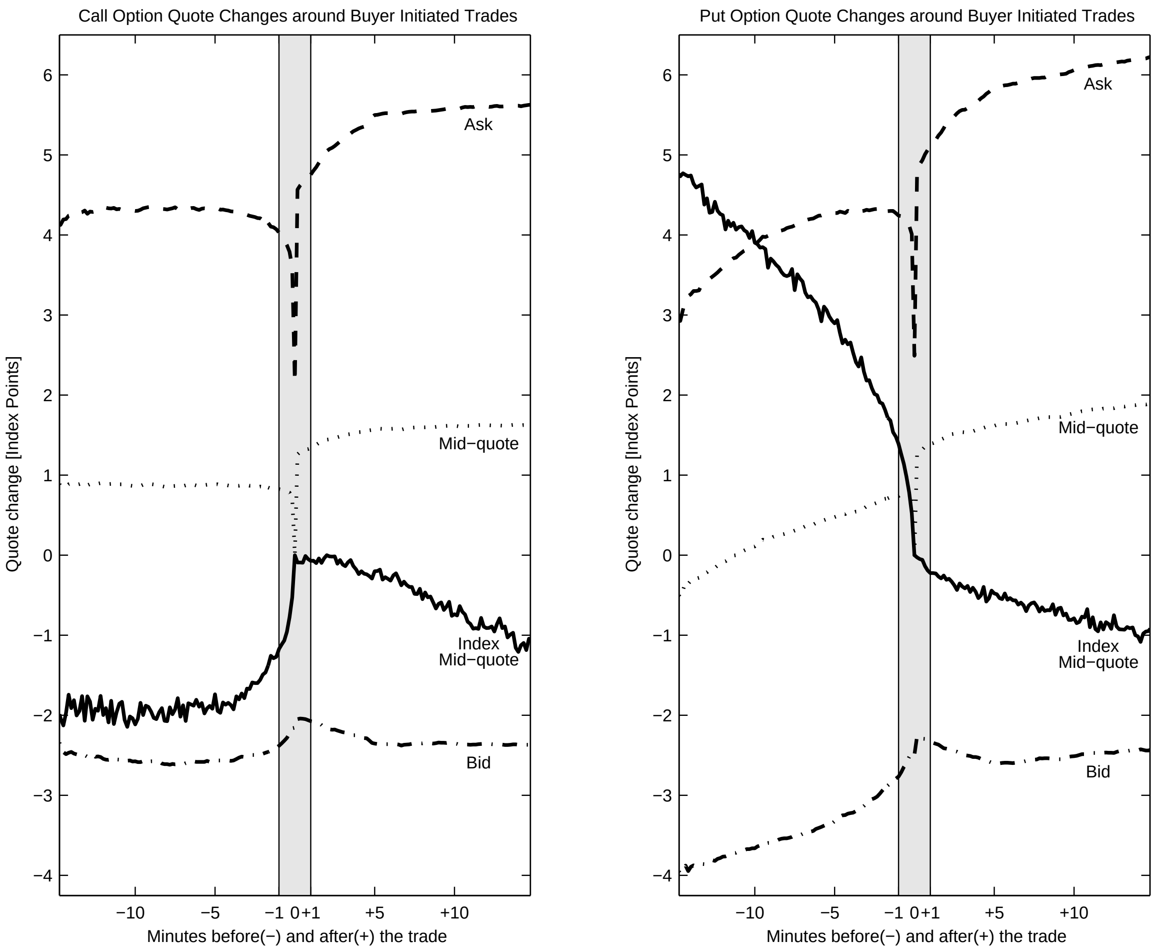

Figure 1: The subplot on the left plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all buyer-initiated trades in the call options. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the trade. The normalized bid quotes series is plotted with a dash-dotted line and the normalized ask quote series with a dashed line. The subplot on the right plots the corresponding quote series for the buyer-initiated trades in the put options.

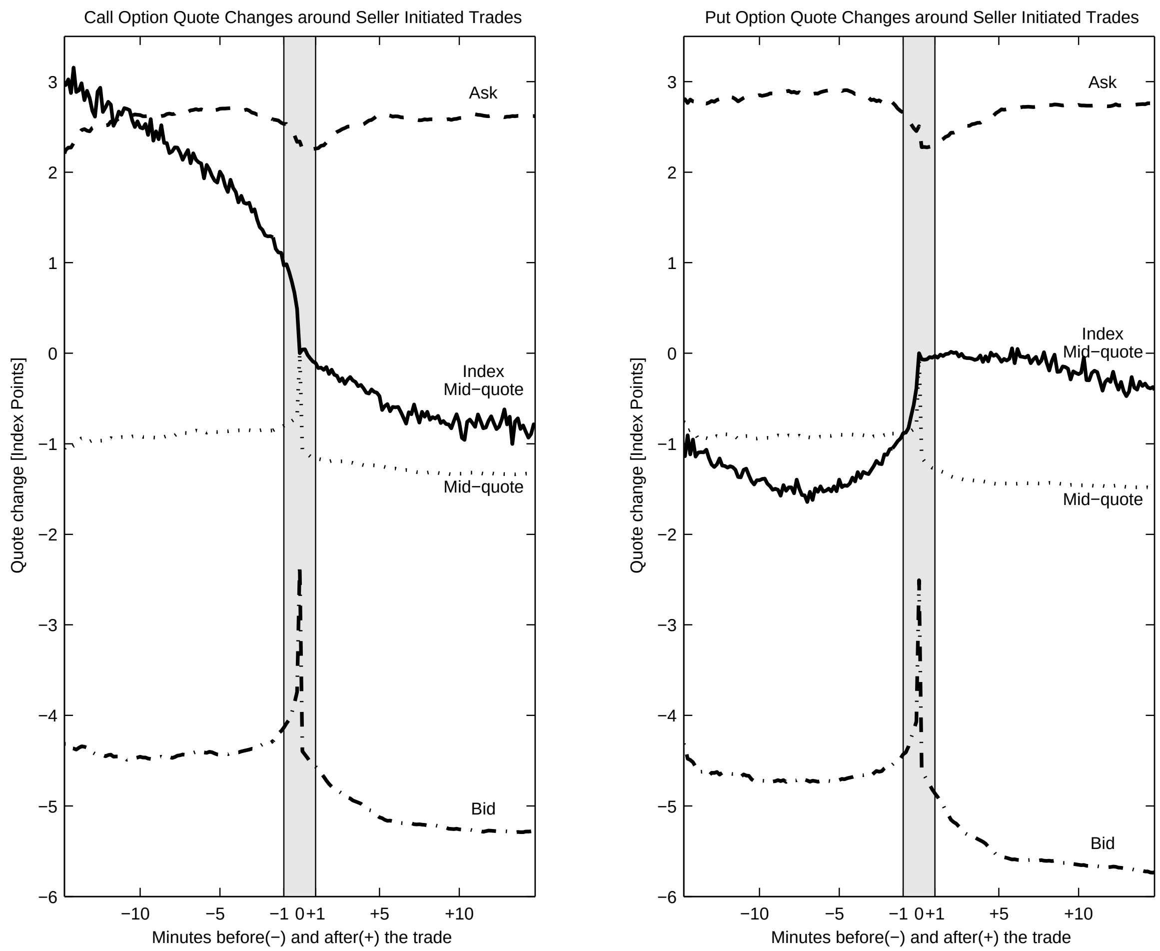

Figure 2: The subplot on the left plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all seller-initiated trades in the call options. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the trade. The normalized bid quotes series is plotted with a dash-dotted line and the normalized ask quote series with a dashed line. The subplot on the right plots the corresponding quote series for the seller-initiated trades in the put options.

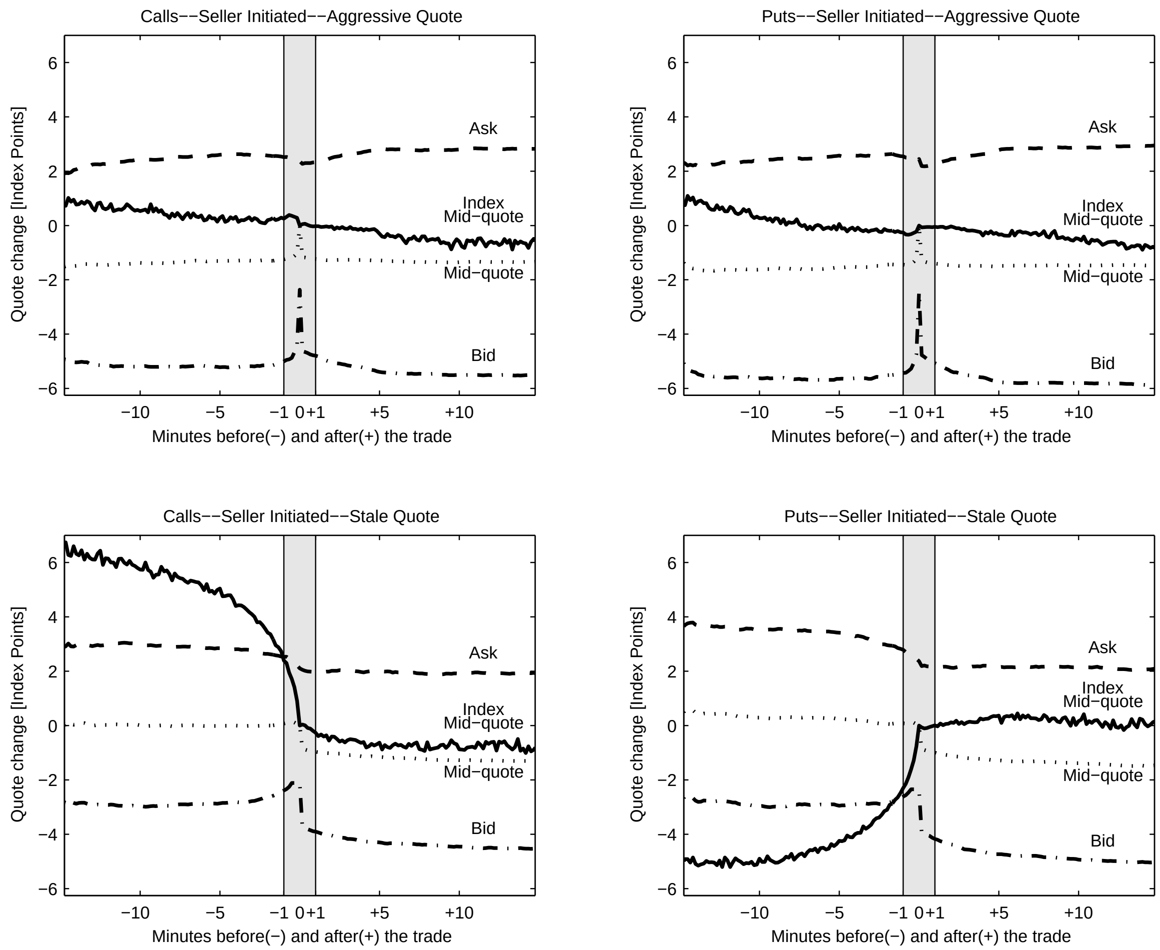

Figure 3: The top left subplot plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all seller-initiated trades in the call options for which the bid quote changed in the last 30 seconds before the trade. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the trade. The normalized bid quotes series is plotted with a dash-dotted line and the normalized ask quote series with a dashed line. The bottom left subplot plots the corresponding series for call options for which the best bid quote did not change in the last 30 seconds before the trade. The subplot on the right plots the corresponding quote series for the seller-initiated trades in the put options for which the ask quote change (top right) and did not change (bottom right).

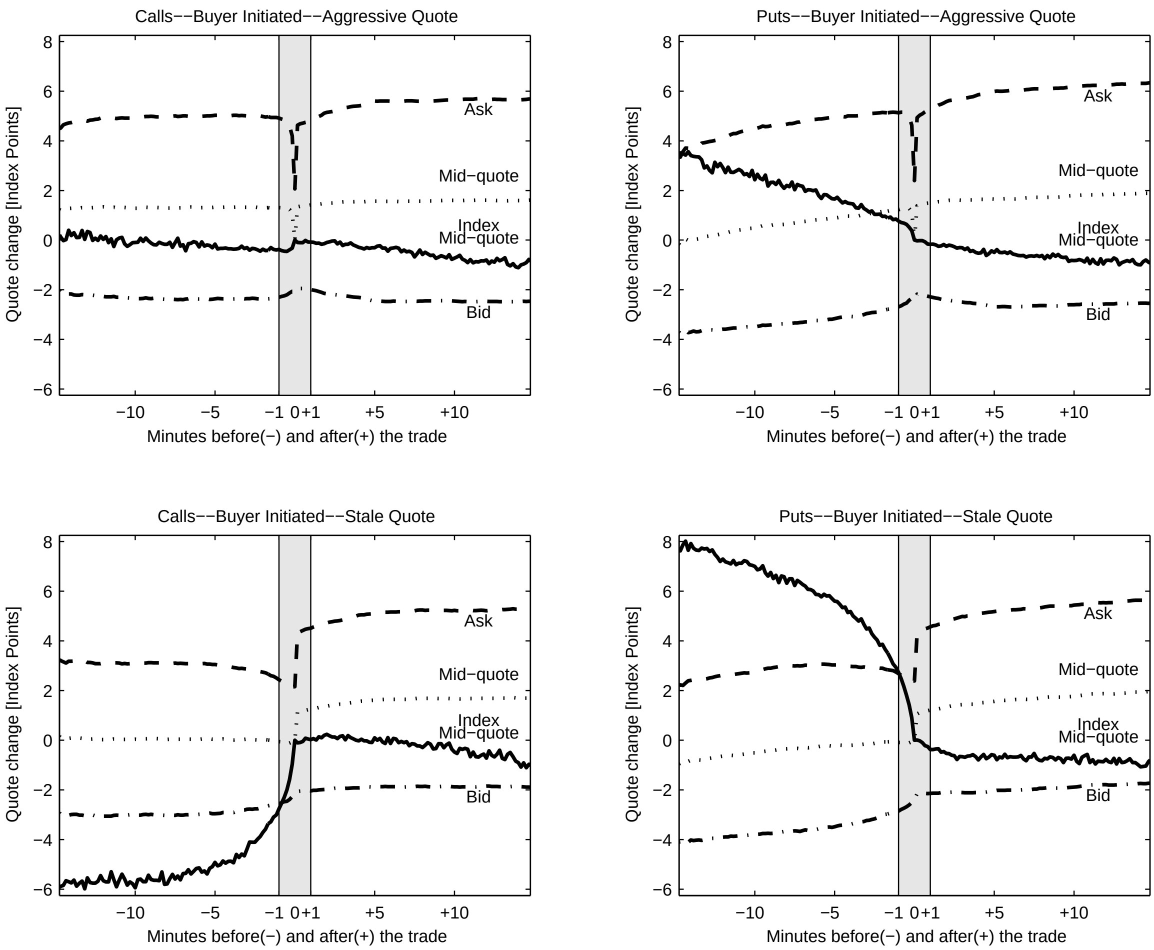

Figure 4: The top left subplot plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all buyer-initiated trades in the call options for which the ask quote changed in the last 30 seconds before the trade. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the trade. The normalized bid quotes series is plotted with a dash-dotted line and the normalized ask quote series with a dashed line. The bottom left subplot plots the corresponding series for call options for which the best ask quote did not change in the last 30 seconds before the trade. The subplot on the right plots the corresponding quote series for the buyer-initiated trades in the put options for which the bid quote change (top right) and did not change (bottom right).