Market Frictions and Seemingly Anomalous Co-Movements of Index Options and Index Futures Quotes*

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Abstract

A call option price is always an increasing and convex function of the underlying asset price whenever the underlying asset price follows a diffusion whose volatility depends only on time and the concurrent asset price—a one-dimensional diffusion. We empirically examine how often the observed quote movements are anomalous in the sense that they imply a violation of either the monotonicity or the convexity property using a sample of quotes and trades of options and futures on the FTSE 100 stock index. We show that such anomalous co-movements are about four times more likely to occur within a minute of an option trade than at other times and are related to the traders' order submissions. We interpret our results as evidence that the seemingly anomalous quote co-movements are driven by market frictions and should not be taken as evidence against option pricing models in the one-dimensional diffusion family. We show that the seemingly anomalous quote co-movements are consistent with traders making rational order submission decisions.

Keywords: Options; Frictions; Market Microstructure; Stale Quotes; Market and Limit Orders

JEL codes: G13; G14; C33

Option pricing theory imposes testable restrictions on the co-movements of option prices and the underlying asset price even when the process for the underlying asset price is not fully specified. Bergman, Grundy, and Wiener (1996) show that when the underlying asset price follows a diffusion whose volatility depends at most on time and the concurrent asset price—a one-dimensional diffusion—then call option prices are always increasing and convex functions of the underlying asset price. Bakshi, Cao, and Chen (2000) report that over short time intervals the co-movements of quotes for S&P 500 index options and futures frequently imply that call prices are decreasing or concave functions of the underlying asset price. They find that neither time decay nor market frictions can completely explain the violations and therefore conclude that the observed co-movements are inconsistent with option pricing models in the one-dimensional diffusion family. We reexamine the seemingly anomalous quote co-movements and report new evidence that links them to market frictions associated with traders' order submissions.

We use a sample of quotes and trades of 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 co-movements of option and futures quotes frequently violate the monotonicity and convexity properties. We extend their analysis by contrasting the violation rates in periods with and without option trades and find large differences. For example, we find that for approximately 9% of all non-overlapping 30-minute intervals the call option and index futures quotes move in the opposite direction and the put option and index futures quotes move in the same direction. For intervals in which a trade occurred, however, the same violation rates are over 16%. For one-minute intervals centered around the time of a trade the differences are even more dramatic; approximately 30% of all option quotes violate the monotonicity property in the one-minute intervals before and after a trade compared with only around 7% of option quotes that are at least a minute away from a trade.

By examining the quote co-movements and the violations in event-time around option trades we identify two scenarios that provide at least a partial explanation for why quote co-movements that violate monotonicity or convexity occur. In the first scenario, 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. In the second scenario, 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 mid-quote is virtually unchanged and is adjusted upwards only after the trade. In the first scenario, the option and the futures quotes move in opposite directions in more than 30% of the observations *both before and after* the trade as the mid-quote is temporarily pushed down before the trade and reverts back after the trade. In the second scenario, the option and the futures quotes move in opposite directions for approximately 12% of the observations *before* and 30% of the observations *after* a trade reflecting the stale quote before the trade and the delayed quote adjustment after the trade. In both scenarios we also observe more frequent violations of the convexity property—in the first scenario the violation rate is 20% and in the second scenario the violation rate is 16%.

Monotonicity and convexity are appealing properties for empirical research because they allow researchers to potentially discriminate between two broad classes of option pricing models without fully specifying the process for the underlying asset price. When the underlying asset price follows a diffusion that depends at most on the time and the concurrent asset price then it is always the case, in a frictionless setting, that the call option price is increasing and convex and the put option price is decreasing and convex in the underlying asset price. On the other hand, when volatility is stochastic or the underlying asset price follows a process that is discontinuous or non-Markovian then a call price that is decreasing or concave in the underlying asset price may arise. Models in the former category include Black and Scholes (1973), Cox and Ross (1976), and Dumas, Fleming, and Whaley (1998). Models in the latter category include stochastic volatility models such as Heston (1993) or jump models such as Bates (1996) or models with heterogenous beliefs such as Buraschi and Jiltsov (2003). We interpret our results as evidence that market frictions play an important role in causing the violations of the monotonicity and convexity properties and that such violations provide at best weak evidence against option pricing models in the one-dimensional diffusion family.

Trading of the FTSE 100 index options and index futures is fully electronic and takes place in a common trading system which means that our sample is not subject to some common measurement issues. First, trades can be classified as buyer- or seller-initiated without error. Savickas and Wilson (2003) document that four commonly used rules for classifying trades as buyer- or seller-initiated correctly classify between 59 and 83 percent of CBOE option trades. Second, option and futures quotes are synchronous, allowing us to determine the exact order and timing of quote changes around trades. Our sample therefore allows us to examine in more detail competing hypotheses for the quote co-movements around option trades.

Both Vijh (1990) and Berkman (1996) examine stock prices movements around the time of large trades in equity options. Vijh (1990) finds no evidence of systematic movements whereas Berkman (1996) finds evidence of systematic stock price changes before the execution of limit orders in the option market. Berkman's evidence is consistent with limit orders, but not the market makers' quotes, being picked off. In our sample all quotes originate from limit orders and we find that for all trade sizes the underlying index futures increase significantly over the 5 minutes *before* buyer-initiated trades in the call options and seller-initiated trades in the put options; similarly the index futures decrease significantly over the 5 minutes *before* seller-initiated trades in call options and buyer-initiated trades in put options. For about 35% of the trades we find that the changes in the index futures that occur before the trade are only fully reflected in the option quotes after the trade consistent with the option quotes being stale.

We find almost no evidence of systematic index futures changes 5 or 10 minutes *after* buyer- or seller-initiated option trades suggesting that there is little adverse selection in the FTSE 100 equity index options market. Our findings differ from recent findings for CBOE equity options. For example, Mayhew, Sarin, and Shastri (1995), Easley, Srinivas, and O'Hara (1998), Chakravarty, Gulen, and Mayhew (2003), and Pan and Poteshman (2003) all report evidence consistent with informed trading in equity options. If most private information is stock specific, it is reasonable to find strong evidence of adverse selection for equity options yet only weak evidence of adverse selection for equity index options. The models of Subrahmanyam (1991) and Gorton and Pennachi (1993) provide a theoretical justification in the context of trading in individual securities and trading in index-based securities.

While standard trade classifications can be made accurately in our sample they are often misleading. We find that a trade that is classified as buyer-initiated frequently occurs after a sell limit order, which undercuts the current best ask quote, is submitted. Arguably, the seller is the one who initiated such a trade because the seller is actively looking to sell the option and it is the buyer who acts as the liquidity provider. Similarly, a trade that is classified as seller-initiated frequently occurs after a new buy limit order, which undercuts the current best bid quote, is submitted. The consequence of the interaction between the limit order submissions and the trades is that standard measures of transaction costs like the effective spread, which ignores the traders' endogenous order submission decisions, are likely to produce misleading results.

The seemingly anomalous co-movements of the option quotes and the index futures quotes do not imply irrational trader behavior. For example, we find that traders who submit aggressive limit orders that undercut the current best bid or ask quotes end up trading at prices that are slightly more favorable than the option mid-quote five minutes after the trade. Such orders are more common when the spread is wider consistent with traders seeking liquidity at a low cost when immediate execution at the existing quotes implies a high cost.

The remainder of the paper is organized as follows. In section 1, we describe the market we study and report some descriptive statistics for our sample. In section 2, we report our empirical results. In section 3, we interpret our findings. In section 4, we conclude and discuss some directions for future research.

1 Description of the Market and the Sample

1.1 The Market

As of May 2000 all trading in financial contracts on Liffe takes place on 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.[1]

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 after the S&P 100 and S&P 500 contracts

[1] The Chicago Board of Trade was reported to trade all of its futures products through its Liffe Connect system provided by Euronext-Liffe according to a Financial Times article by Jeremy Grant on January 3, 2004 entitled "CBOT starts up new system." The Chicago Mercantile Exchange was reported to be in talks with Euronext-Liffe to license the Liffe Connect system in a Securities Industry News article by Isabelle Clary on November 17, 2003, entitled "CME looks at Liffe Connect Platform."

of the CBOE and the ODAX contract of the Eurex.

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. Strike prices for the European-style FTSE 100 index options are set at values that end on 25 and 75 index points for contracts with 90 days or less to maturity and that end on either 25 or 75 index points for contracts with more than 90 days to maturity.[2]

A new expiration month starts trading with a minimum of eleven strike prices, set around the current index value. Additional strike prices are opened for trading after the index rises above the second highest, or falls below the second lowest, strike price that is currently open. The standard expiration months are March, June, September and December. Additional expiration months are introduced so that contracts that expire during the three nearest calendar months are always available. The FTSE 100 index futures contract is traded with expiration months that match the three nearest standard expiration months above.

The trading hours are 8:00 a.m. to 4:30 p.m. Trader submit orders 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 proportion to the volume. The exception to the pro rata allocation is that the order with the highest time priority receives a fill that is subject to a minimum and a maximum volume condition. Orders can be cancelled at any time, and all orders except good-until-cancelled orders are cancelled automatically at the market close.

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.

Customers may submit orders by calling a member firm, but they may also submit orders without any direct intervention by a member. Customers may set up order routing software to

[2]American-style options on the FTSE 100 index are also traded on Liffe with strike prices that end on either 50 or 100 index points. Because the American-style options are inactively traded, and because of the possibility of early exercise, we use only data on the European-style options.

electronically route orders via a member directly to Liffe Connect. Traders may also use software, known as automated price injection models, that automatically generates order submissions or cancel outstanding orders.

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. Customers who are not members may obtain the same information from quote vendors. In contrast, no information on the identity of members submitting orders is distributed. Trading is anonymous both before and after a trade. The buyer and the seller each pay a fixed cost of £0.25 per trade.

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.

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 and all trades involve a market order executing against a limit order.

We dropped all observations from our sample that violated 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 no 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 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. 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; quote updates outnumber total trades by 140 to 1 for call options and 113 to 1 for put options whereas the ratio for index futures is close to 2 to 1.

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 6 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.

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. Overall, it is difficult to predict the index futures price changes based on past price changes beyond a very short horizon.

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 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.

2 Basic Properties of Option Prices

Bergman, Grundy, and Wiener (1996) extend previous no-arbitrage results in Merton (1973) and Cox and Ross (1976) by showing 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.

The bounds on the option's delta imply that certain co-movements of options prices and the underlying asset price are inconsistent with models where the underlying asset price follows a one-dimensional diffusion but may be consistent with models where the underlying asset follows a discontinuous process or a process with stochastic volatility. The bounds can therefore be used as one way to distinguish between different classes of models.

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 Equations 1 and 2*

$$
\begin{array}{ll}
\textit{Type I} : & \left\{ \begin{array}{lll} \frac{dC}{dS} < 0 & \textit{and} & dS \neq 0, \\ & \textit{or} & \\ \frac{dP}{dS} > 0 & \textit{and} & dS \neq 0. \end{array} \right. \\
\textit{Type II} : & \left\{ \begin{array}{lll} dS \neq 0 & \textit{and} & dC = 0, \\ & \textit{or} & \\ dS \neq 0 & \textit{and} & dP = 0. \end{array} \right. \\
\textit{Type III} : & \left\{ \begin{array}{lll} dS = 0 & \textit{and} & dC \neq 0, \\ & \textit{or} & \\ dS = 0 & \textit{and} & dP \neq 0. \end{array} \right. \\
\textit{Type IV} : & \left\{ \begin{array}{lll} \frac{dC}{dS} > 1 & \textit{and} & dS \neq 0, \\ & \textit{or} & \\ \frac{dP}{dS} < -1 & \textit{and} & dS \neq 0. \end{array} \right.
\end{array} \tag{3}
$$

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 has changed. 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.[3]

[3] 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.

3 Empirical Results

3.1 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 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 violation 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 since it simply implies that option quotes tend to change around the time of option trades. What is more surprising is that anomalous quote co-movements are more common in periods when the options are traded.

To determine whether the anomalous quote co-movements are really associated with option trades, we recalculate the violation rates for finer time intervals. 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 more than three 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 trade offering more evidence that the violations are linked to trading. 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 is 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.

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 is that option trades are more likely after larger changes in the index. Another is that large index changes are more likely after option trades. In the next section we examine both possibilities.

3.2 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 relatively 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 reflect 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 revision 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 hypothesis:

Hypothesis 1 *Option trades are non-informative:*
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.

$$\begin{aligned}
E\left[C_{t+\tau} - C_t \middle| \text{ buyer-initiated trade in call option at } t\ \right] &= 0 \\
E\left[C_{t+\tau} - C_t \middle| \text{ seller-initiated trade in call option at } t\ \right] &= 0 \\
E\left[P_{t+\tau} - P_t \middle| \text{ buyer-initiated trade in put option at } t\ \right] &= 0 \\
E\left[P_{t+\tau} - P_t \middle| \text{ seller-initiated trade in put option at } t\ \right] &= 0
\end{aligned}$$

Table 6 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 6 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. Hypothesis 1 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 6 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 hypothesis:

Hypothesis 2 *No adverse selection:*
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.

$$E\left[\Delta_t^{call}(F_{t+\tau} - F_t)|\ \textit{buyer-initiated trade in call option at } t\right] \leq 0$$
$$E\left[\Delta_t^{call}(F_{t+\tau} - F_t)|\ \textit{seller-initiated trade in call option at } t\right] \geq 0$$
$$E\left[\Delta_t^{put}(F_{t+\tau} - F_t)|\ \textit{buyer-initiated trade in put option at } t\right] \leq 0$$
$$E\left[\Delta_t^{put}(F_{t+\tau} - F_t)|\ \textit{seller-initiated trade in put option at } t\right] \geq 0$$

Table 7 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 Hypothesis 2. 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 6 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 hypothesis:

Hypothesis 3 *No stale quotes:*

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.*

$$
\begin{aligned}
E\left[\Delta_t^{call}(F_t - F_{t-\tau})|\ \textit{buyer-initiated trade in call option at } t\right] &\leq 0 \\
E\left[\Delta_t^{call}(F_t - F_{t-\tau})|\ \textit{seller-initiated trade in call option at } t\right] &\geq 0 \\
E\left[\Delta_t^{put}(F_t - F_{t-\tau})|\ \textit{buyer-initiated trade in put option at } t\right] &\leq 0 \\
E\left[\Delta_t^{put}(F_t - F_{t-\tau})|\ \textit{seller-initiated trade in put option at } t\right] &\geq 0
\end{aligned}
$$

Table 8 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.[4] In all cases the mean changes are positive for buyer-initiated trades and negative for seller-initiated trades. We reject Hypothesis 3 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 6 are actually implied by index futures changes before the trades occur.

Overall, the results in Table 6 together with the results in Tables 7 and 8 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.

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 the options quotes at the time of a trade are at least partly stale. From Table 8 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 hypothesis:

Hypothesis 4 *Partial quote revision:*

The expected change in the option's mid-quote from τ minutes before a trade to the time of a trade

[4]The number of observations and the mean spreads differ slightly between Table 8 and Table 7 because some observations lack valid quotes either before or after a trade.

is non-positive for a buyer-initiated trade and non-negative for a seller-initiated trade.

$$E[C_t - C_{t-\tau}| \text{ buyer-initiated trade in call option at } t \,] \geq 0$$

$$E[C_t - C_{t-\tau}| \text{ seller-initiated trade in call option at } t \,] \leq 0$$

$$E[P_t - P_{t-\tau}| \text{ buyer-initiated trade in put option at } t \,] \geq 0$$

$$E[P_t - P_{t-\tau}| \text{ seller-initiated trade in put option at } t \,] \leq 0$$

Table 9 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 8 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. Hypothesis 4 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 for what exactly happens 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.

3.3 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 7 and 8 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.

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 8. The relatively small changes in the index futures mid-quote after a trade are consistent with the results in Table 7.

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, at least partly, before the buyer-initiated trade. Similarly for seller-initiated trades the decrease in the mid-quote after a trade is partly driven by the a decrease in the bid quote. The above evidence is consistent with the quotes being stale at the time of the trade.

But the discrete negative jump in the ask quotes within the last minute before a buyer-initiated trades and the discrete positive jump in the bid quote before seller-initiated trades are not consistent with stale quotes. The plots show why Hypothesis 4 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 quote 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 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.

3.3.1 Aggressive Quotes versus Stale Quotes

To further test for stale quotes, 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.[5] 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 options, and 37% of all put options.

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

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

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.

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 seems to be 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 violations rates differ for trades associated with aggressive and stale quotes.

3.3.2 Frequency of Violations Revisited

Table 10 reports the Bakshi, Cao, and Chen 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 10 shows that there is a considerable difference in violations within the two one-minute intervals surrounding the trade once a separation of trades into stale quote trades and aggressive quote trades has been made. 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 quote updates are violating both the monotonicity and the convexity property when they get adjusted to the considerable index movement that we saw in Figures 3 and 4. We can see from the last six rows of the call and put panel of Table 10 that aggressive quotes violate the monotonicity and convexity properties both pre- and post trade in approximately the same frequencies. This seems to make sense because the aggressive quotes are submitted somewhat 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. This is further evidence that many of the violations are caused by market frictions, i.e. the strategic behavior of market participants seeking liquidity.

3.3.3 Is there an Economic Rationale for the Trader Behavior?

One way to judge whether the trader behavior can be rationalized is to examine the transactions costs associated with the traders' strategies. Table 11 reports the quoted and realized spreads for buyer- and seller-initiated trades classified into two categories depending on whether an aggressive quote or a stale quote was the passive side of the trade. The top panel reports the results for calls and the bottom panel reports the results for puts.

The average quoted spreads at one-half minute before the trade and at the time of the trade are reported in the second and third columns. For the aggressive quote categories the quoted spread narrows by about £1.5 from one-half minute before the trade to the time of the trade. At the time of the trade the quoted spreads are indistinguishable for the two categories. One interpretation of the aggressive quotes is therefore that traders who seek liquidity submit aggressive limit orders that narrow the spread when the spread is wider than normal.

The average realized spread is reported in the fourth column. The average realized spread is between +£0.5 and +£1 implying that while the liquidity providers earn less than the quoted spread they do earn, on average, a positive gross spread on all trades including trades that occur when their quotes are stale.

The average change in the option value implied by the index futures change from ten minutes before the trade to the time of the trade is reported in the fifth column. When the trade is against a stale quote we observe an average implied change of £1.6 for calls and £2.00 for puts whereas before seller-initiated trades we observe an implied change of -£1.30 for calls and -£1.64 for puts. When the trade is against an aggressive quote the implied changes are smaller on average and for seller-initiated trades the average changes are close to zero.

The last two columns of the table report the changes in the option mid-quotes from one-half minute before the trade to ten minutes after the trade as well as from the time of the trade to ten minutes after the trade. For both categories of trades we observe an upward shift in the option mid-quote of approximately £1.7 after buyer-initiated trades and a downward shift of approximately £1.4 after seller-initiated trades. In both cases a form of quote staleness explains the mid-quote changes. The difference is that in the aggressive quote case the stale quote is the result of a trader's active decision to place an aggressive order whereas in the stale quote case the stale quote results from the passive decision of a trader to not cancel or revise an existing limit order. The end-result is that, on average, the passive side of the trade earns a small, but positive, gross spread of £0.5 to £1 or approximately 30% of the quoted spread. Thus, there is not necessarily anything irrational about the behavior of the passive side of the trade in either case.

4 Conclusions

We re-examine the seemingly anomalous co-movements of index option and futures quotes first documented in Bakshi, Cao, and Chen (2000) and report new evidence that market frictions play a bigger role than previously thought. In particular, we find that the interaction between the order book and the traders' order submission strategies often generate co-movements that seem to imply that a call option price is either decreasing or concave in the underlying index value.

We focus on the co-movements around the trades because the anomalous co-movements that imply either that call prices are decreasing or concave in the underlying are approximately twice as likely in 30 minutes intervals in which a trade occurs than in 30 minute intervals in which no trade occurs; for shorter intervals around trades the difference is even bigger. We document that traders often place aggressive limit orders that undercut the current best bid or ask quotes and often move the option mid-quotes in the 'wrong' direction compared to the concurrent movements in the underlying index. Presumably such aggressive limit orders also fail to execute in some instances leading to an anomalous co-movement without a subsequent trade.

Our evidence suggest that a model of option trading should allow for the distribution of traders' reservation prices for buying or selling the options to depend on movements in the underlying index and for traders to choose between market and limit orders. A model may be used to decompose the observed co-movements of index options and index futures quotes into a frictions-driven component and a true component. Such a decomposition may be useful for methods that use high-frequency data to perform option pricing and hedging. For example, Bossaerts and Hillion (1997, 2003) develop hedging and pricing methods that are based on co-movements of DAX index option and index futures measured over 1.5 hour intervals. Bossaerts and Hillion (2003) report that while their method performs well for pricing the options it performs poorly when used to hedge the options. They show that the poor performance is driven by the anomalous co-movements of the options and the underlying index and suggest price jumps as a possible explanation. An alternative interpretation based on our findings is that a method for removing the effect of market frictions is needed to get an accurate estimate of the co-movements. We leave such tasks for future research.

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Table 1: **Descriptive Statistics**

	Call Options		Put Options		Index Futures	
Variable	Mean	Std.Dev.	Mean	Std.Dev.	Mean	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 0.00.

Table 3: **Mean Violation Rates**

Call Options	N	Type [%] I	II	III	IV	Total
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	Type [%] 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**

Monyeness		Time to Expiration 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: **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 7: **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 8: **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 9: **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 10: **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.

Table 11: **Quoted and Realized Spreads and Mid-quote Changes Around Trades**

Time/Time Interval		N	Quoted Spread -0.5	Quoted Spread 0	Realized Spread 10	Delta× Index Change -10 to 0	Option mid-quote change -0.5 to 10	Option mid-quote change 0 to 10
Call Options								
Buyer Initiated	Aggressive Quote	8,641	3.61	2.06	0.45	0.31	0.27	1.61
	Stale Quote	4,728	2.38	2.37	0.49	1.59	1.88	1.73
	Difference		1.23**	-0.16	-0.04	-1.28**	-1.62**	-0.12
Seller Initiated	Aggressive Quote	9,561	3.76	2.37	0.97	-0.08	-0.17	-1.40
	Stale Quote	4,461	2.38	2.21	0.79	-1.30	-1.59	-1.42
	Difference		1.38**	0.16	0.18	1.22**	1.42**	0.02
Put Options								
Buyer Initiated	Aggressive Quote	10,298	3.85	2.31	0.50	0.99	0.68	1.81
	Stale Quote	6,063	2.57	2.43	0.63	2.00	1.94	1.80
	Difference		1.28**	-0.11	-0.13	-1.00**	-1.26**	0.01
Seller Initiated	Aggressive Quote	10,732	3.83	2.30	0.86	-0.05	0.00	-1.44
	Stale Quote	5,861	2.56	2.41	0.90	-1.64	-1.66	-1.51
	Difference		1.27**	-0.11	-0.11	1.59**	1.65**	0.07

The table reports the mean quoted and realized spreads for buyer and seller initiated trades in call and put options split into two groups—aggressive quote and stale quote—depending on whether or not there was a change in the best ask quote (buyer-initiated) or best bid quote (seller-initiated) within the last 30 seconds before the trade. The mean quoted spread is reported both at 30 seconds before the trade (Time=-0.5) and at the time of the trade (Time=0). The realized spread is computed using the signed transaction price and the mid-quote at 10 minutes after the trade. The last three columns of the table report the mean changes from 10 minutes before the trade to the time of the trade for the index futures multiplied by the option's delta and the mean change in the option's mid-quote from 30 second before the trade and from the time of the trade to 10 minutes after the trade. For all mean spreads and mean quote changes the difference between the mean for the observations with a quote change and the observations with no quote change are reported on the row labeled 'Difference' with ** indicating that the difference is statistically significant at the 1% level or better.

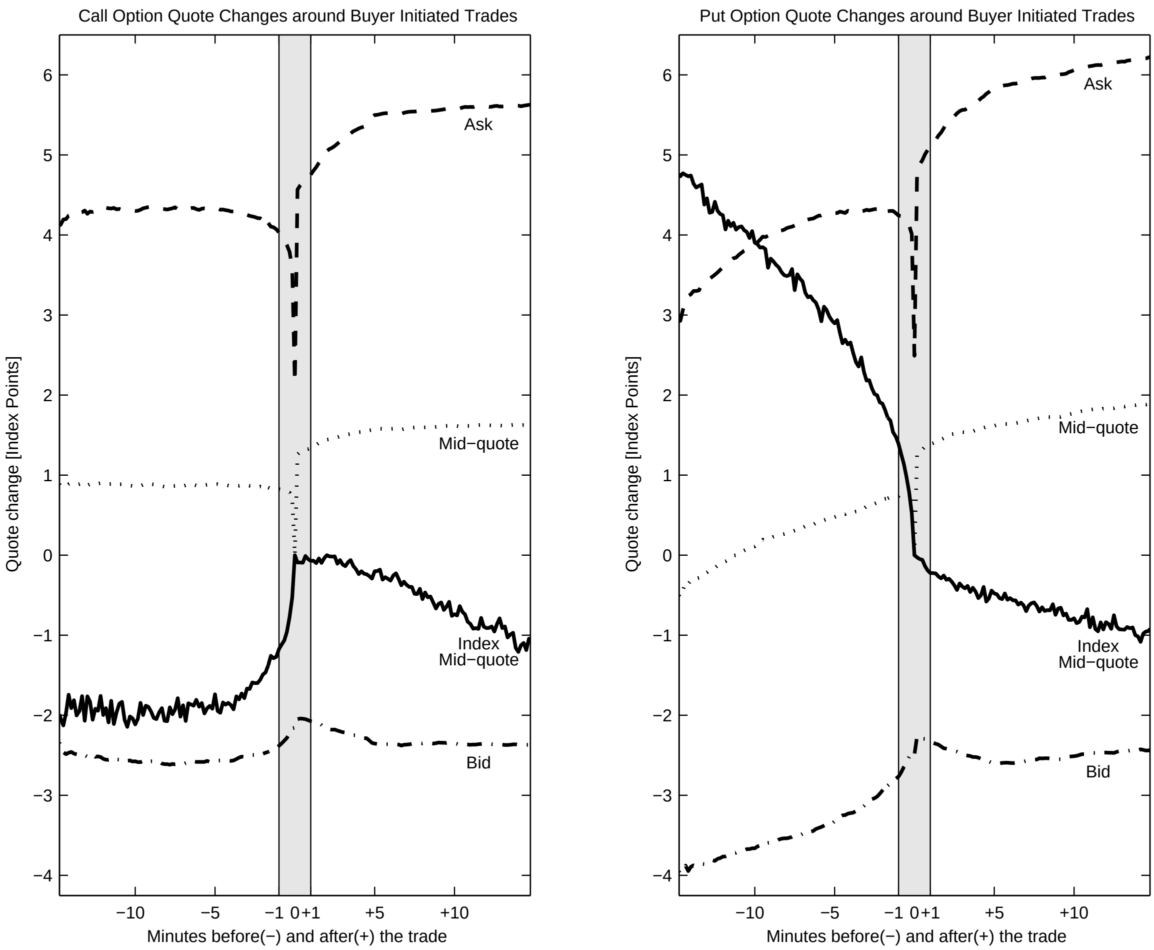

Figure 1: The subplot on the left plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all buyer-initiated trades in the call options. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the 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.

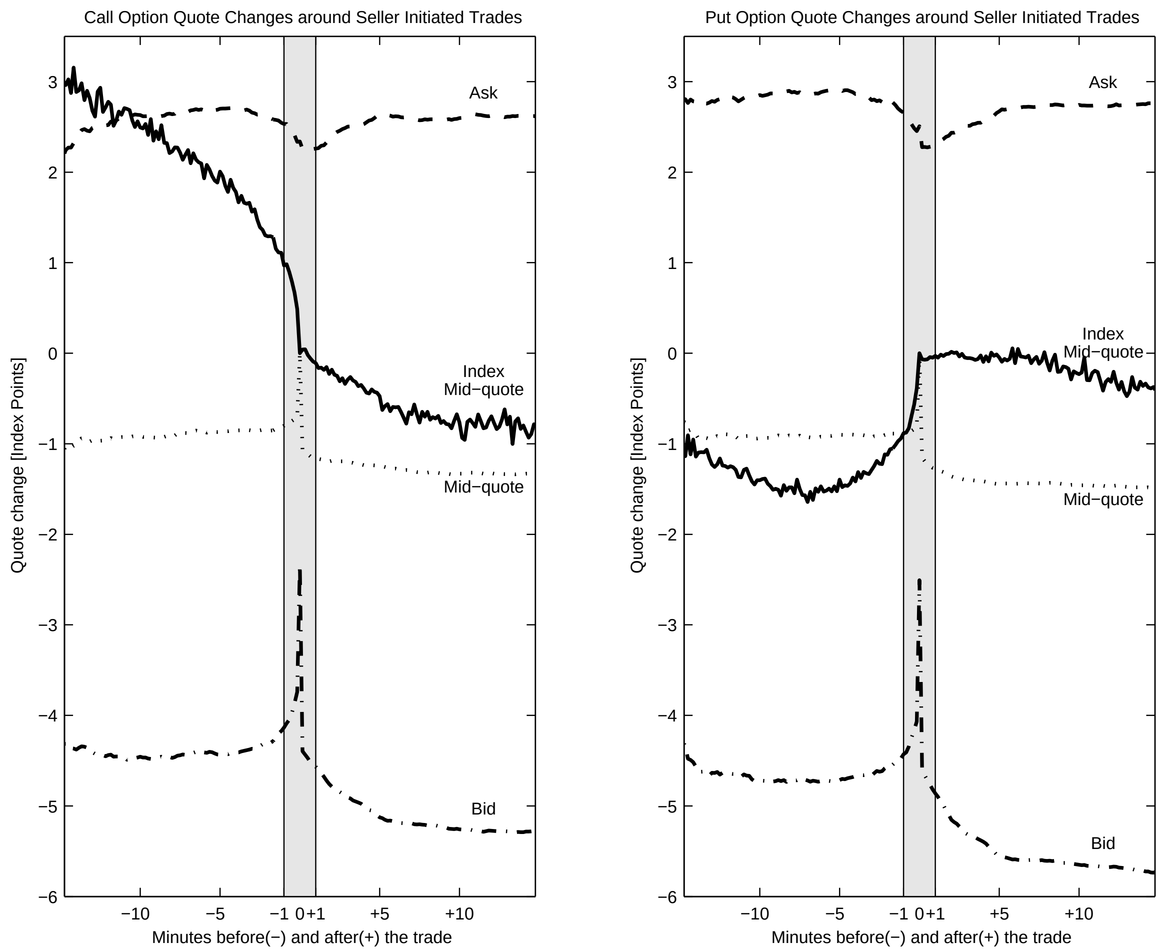

Figure 2: The subplot on the left plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all seller-initiated trades in the call options. The series of mid-quotes are normalized by subtracting the respective mid-quote values at the time of the 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.

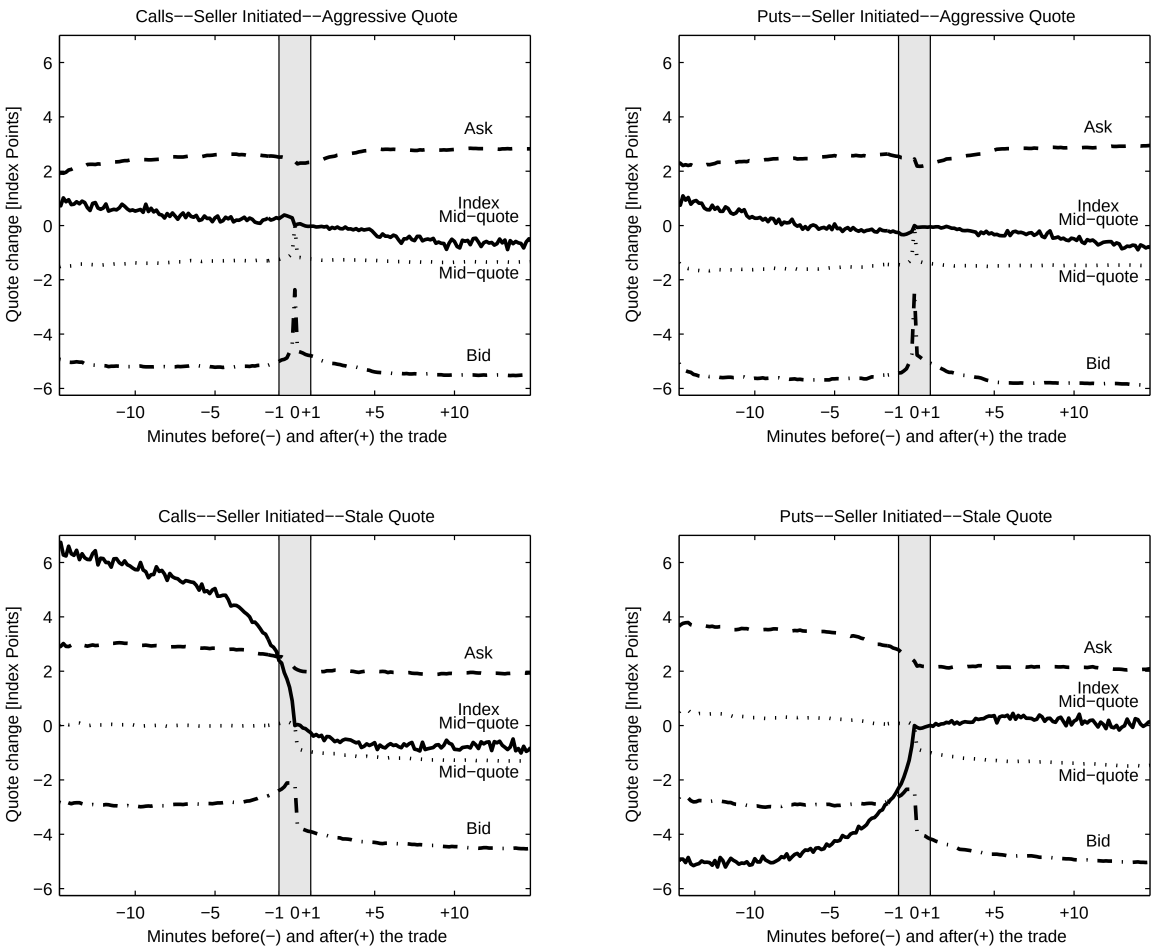

Figure 3: The top left subplot plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all seller-initiated trades in the call options for which the bid quote changed in the last 30 seconds before the trade. The series of mid-quotes are normalized 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).

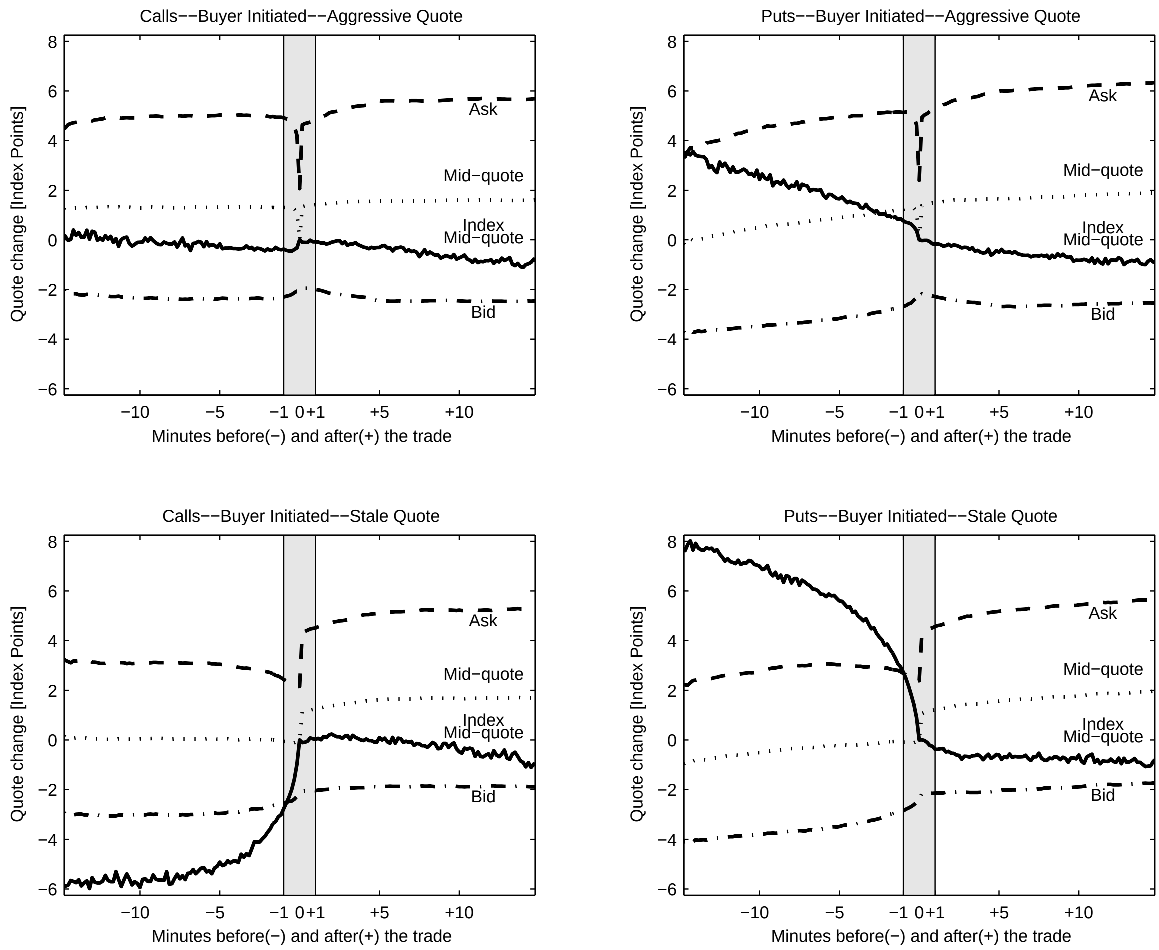

Figure 4: The top left subplot plots the normalized series of the mid-quotes for the index futures (solid line) and the option (dotted line) for all buyer-initiated trades in the call options for which the ask quote changed in the last 30 seconds before the trade. The series of mid-quotes are normalized 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).