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A new measure of the direction and timing of information flow between markets[1]

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Abstract

This paper examines the direction and timing of the flow of information between CBOE call options and the underlying NYSE stocks using a new methodology that avoids potential biases that can be introduced by using fixed-length time intervals. For the stocks in the sample, stock quotes tend to lead option quotes, but the length of the lead, ranging from a few seconds to six minutes, is shorter than previously thought. Options also occasionally lead stocks, but there is no evidence that the option lead exceeds three minutes. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

This study investigates the direction and timing of the flow of information between the Chicago Board Options Exchange (CBOE) and the New York Stock Exchange (NYSE) for call options and the underlying stocks. The analysis is motivated by previous studies that provide conflicting evidence concerning the question of whether the options market leads or follows the stock market. Manaster and Rendleman (1982) use daily prices and conclude that options lead the underlying stocks by as much as a full day, while Stephan and Whaley (1990)

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use five-minute intervals and conclude that stocks lead options by at least 15 minutes. Chan et al. (1993) use five-minute intraday quotes and argue that the stock lead found by Stephan and Whaley is spurious and can be explained by their use of transactions prices. While these studies employ various measures of information flow between the two markets and arrive at conflicting conclusions, they all share one thing in common: the use of fixed time intervals for measuring information flow.

The time between stock and option-quote formation and dissemination to other exchanges is typically measured in seconds, and quotes in one market can be adjusted to reflect changes in quotes in other markets almost instantaneously. Since there are virtually no direct costs associated with changing quotes, the structure of the stock and options markets suggests that any systematic leads will be shorter than five minutes. Fixed intervals short enough to measure leads less than five minutes cannot, however, be used without creating potentially serious biases; the frequency of stock and option transactions is simply too low. Using five-minute (or longer) intervals will tend to obscure leads that are less than five minutes, and may incorrectly lead to the conclusion that neither market leads. While leads shorter than five minutes are not likely to represent arbitrage opportunities, the presence of such leads could provide important information concerning market preferences for informed traders.[2]

This study employs a new methodology involving the construction of variable-length return intervals for call options and the underlying stocks. The method is designed to detect leads that are shorter than five minutes, and accurately measure lead lengths. Allowing the length of the return intervals to vary with the frequency of market activity avoids potential biases created by the presence of intervals with no trading activity, and allows for the unambiguous identification of leads that previous studies classify as contemporaneous price changes. The results show that stock quotes tend to lead option quotes, although some information flows from the stock exchange to the options exchange. The length of the leads, however is short: The stock lead ranges from a few seconds to six minutes, and the options lead is never longer than three minutes.

The potential problems that can arise when fixed intervals are used to identify the direction and timing of stock and option leads are introduced in Section 2. The data used are described in Section 3, summary statistics are presented in Section 4, and Section 5 contains the results of standard fixed-interval regressions. Section 6 describes the variable-length interval methodology, and the variable-interval results are presented in Section 7. Section 8 concludes the paper.

[2] See Easley et al. (1998) for additional references on empirical studies of the direction and timing of information flow and a microstructure model of market choice.

2. Fixed versus variable time intervals

Previous empirical studies of lead-lag relations between the options and stock markets compare option and stock transaction prices, quotes, or volume changes using fixed intervals. The last option trade or quote occurring in a particular interval is used as the representative price for that interval, and if no trade or quote is registered during a particular interval, transactions from previous intervals are typically applied to the empty intervals. While the problems caused by assigning asynchronous closing prices to daily intervals are well understood, the use of shorter intra-day fixed intervals can also distort underlying trading patterns and lead to incorrect statistical inferences.

One condition under which incorrect inferences are likely is when the length of the fixed interval is long relative to the length of the lead. If the time required for traders in one market to react to information in the opposite market is less than the interval length, using fixed intervals may obscure any leads that are present and lead to the incorrect conclusion that information is reflected simultaneously in the two markets.

Intervals that are too long can also lead to biased estimates of lead lengths. Suppose, for example, that the stock consistently leads the option by 30 seconds and five-minute fixed time intervals are constructed. A sufficiently large sample would contain enough observations where the stock-price change is assigned to one interval, and the option-price change is assigned to the next interval, to suggest a five-minute lead. Reducing the length of the interval to avoid biased lead-length estimates will increase the number of intervals with missing observations, creating other problems. Measurement error caused by missing observations will affect the consistency and efficiency of coefficient estimates.

Significant leads may also be found where none exist. If option transactions occur less frequently than stock transactions, intervals with missing option prices will occur more frequently than intervals with missing stock prices, and tests will be biased toward concluding that the stock market leads the options market. The opposite will tend to occur when option transactions are more frequent than stock transactions.[3]

To measure leads that may be shorter than five minutes, while avoiding the potential biases that are likely to be induced by missing intervals, this study uses ordered quote changes in the stock and option markets to construct

[3] Determining an optimal interval length that is neither too long nor too short would seem to provide a simple solution to these problems, but stock and option trading does not occur uniformly throughout the day. Because of the U-shaped trading patterns observed for both stocks and options (see, for example, Stephan and Whaley, 1990), intervals that are short enough to accommodate the high volume near the open and close will have missing values during the middle of the day, and intervals that are long enough to accurately reflect mid-day trading patterns will obscure much of the trading activity that occurs near the open and the close.

variable-length price-change intervals. Option-quote intervals are constructed whenever a new quote is registered so that the length of each interval is determined by the actual time between quotes. Similarly, the lengths of leading and lagged stock-quote intervals are determined by the time between quotes in the stock market. Since the stock and option quote changes are ordered by time, the ambiguity introduced by using the last quotes recorded during a fixed interval is eliminated. Stock-quote changes either lead or follow call-quote changes; by construction there are no contemporaneous quote changes. This is consistent with the way quotes are recorded. Quotes in the stock and options markets are rarely recorded during the same second; it is almost always possible to determine whether an option quote or a stock quote is recorded first. While the fixed-interval approach artificially assigns quotes recorded at different times to the same interval, this study uses the recorded sequence of quotes to unambiguously determine whether stock-quote changes precede or follow call-quote changes.[4]

3. Data

The sample period is the 41 trading days of November and December 1990. The sample is limited to the ten underlying stocks with the largest number of call-option quotations. Limiting the sample to a small number of stocks is dictated by the use of Generalized Method of Moments estimates in the time-series regressions; computational limitations make a larger sample impractical. Using the stocks with the most actively quoted options facilitates comparisons with previous studies, but the methodology employed in this study is suitable for even the most thinly quoted stocks and options.

The options data are extracted from the Berkeley Options Data Base, and the stock data are obtained from the Institute for the Study of Security Markets' (ISSM) Equity Transactions File. Bid–ask quote midpoints are used for the options and underlying stocks because they tend to provide a more timely measure of information flow than trade prices. In addition to quotes, ex-dividend dates, dividend amounts, and riskless rates are also required for estimating implied hedge ratios. The ex-dividend dates and dollar dividends for the ten underlying stocks in the sample are taken from the CRSP Daily Master File, and the riskless rates are obtained from a set of maturity-matched Treasury-bill quotes provided by Morgan Stanley.

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[4] The problem of asynchronous quotes inherent in the fixed-interval approach might also be addressed by using proportional hazards (Cox) regressions to model the time between quotes, and then conditionally estimating the relation between quote changes in the two markets. While this may offer a promising approach in future studies, without information on orders in both markets, the explanatory power of proportional hazards regressions for the data used in this study is too low to make this approach practical.

4. Summary statistics

Table 1 provides summary measures of daily trade and quote frequency for each of the ten stocks in the sample, and for all call options listed for each of the underlying stocks.[5] Trades and quotes occur more frequently for the stocks than the calls, and it is interesting to note that while trades occur more frequently than quotes for the stocks in the sample, the opposite is true for call options. Further analysis reveals that the times between stock quotes and stock trades exhibit the pronounced U-shaped pattern found for trading volume in previous studies: stock trades and quotes occur more frequently near the open and the close than during the middle of the day. A U-shaped pattern is also present for the options, although the increase in trade and quote frequency near the close is less pronounced for the options than for the underlying stocks. Mean times between option quotes and trades are less than five minutes near the open, and greater than five minutes later in the day, suggesting that the five-minute fixed-intervals used by Chan et al. (1993) may lead to incorrect inferences concerning the lead-lag structure in the two markets.

Five-minute fixed-interval series are also constructed for each stock and each call option, using the last quote recorded before the end of the interval as the representative quote for the interval. Table 1 shows the percentage of non-missing quote intervals for the calls and the underlying stocks. During the sample period, an average of 22% of the five-minute stock-quote intervals have missing values, and more than 80% of the five-minute option-quote intervals do not contain quotes.[6] When the call-option sample is limited to the strikes and maturities that tend to be most actively traded, more than half of the intervals still contain missing observations.[7]

5. Fixed-interval regression results

The data described above are used to construct fixed-interval time series with interval lengths of five minutes, 15 minutes, 60 minutes, and one day. Following

[5] Throughout the remainder of the paper, all option-quote changes are for call options with the same underlying stock, maturity, and strike price. The times between option quotes and trades in Table 1 are the mean times between quotes and trades for contracts with matched maturities and strike prices.

[6] The mean time between call-option quote-changes may not appear to be consistent with the reported percentage of non-missing intervals. For example, while the mean time between quotes for IBM calls is only 4.32 min, 64.2% of the intervals contain missing values. While this is partially due to quote clustering, the main reason for the apparent discrepancy is that all listed options are equally weighted in constructing the fixed intervals. The most active options, with lower times between quotes, are therefore more heavily weighted in calculating the mean time between quotes.

[7] The most active option sub-sample is restricted to calls with no more than 60 days left to maturity, either at or out-of-the-money by no more than five percent of the strike price.

Table 1
Stock and option trade and quote frequency summary statistics[a]

Ticker	Stock			All call options			Most active calls	
	Mean time between trades	Mean time between quotes	Non-missing five-minute intervals (%)	Mean time between trades[b]	Mean time between quotes[b]	Non-missing five-minute intervals (%)	Mean time between quotes[b]	Non-missing five-minute intervals (%)
BA	1.29	1.99	78.7	16.00	13.44	15.3	4.9	42.3
CCI	0.84	2.18	73.1	16.39	13.75	17.3	7.3	35.8
GE	0.65	1.22	89.3	15.68	10.75	17.5	3.6	50.0
IBM	0.75	0.76	95.4	7.19	4.32	35.8	1.1	85.2
MRK	1.24	1.95	77.7	20.24	12.74	21.2	5.7	43.3
NCR	1.32	1.77	80.6	13.52	11.08	13.4	3.4	44.9
PCI	1.76	3.25	67.2	23.42	9.41	27.9	3.9	55.4
UAL	2.94	3.13	64.6	23.74	16.65	9.6	4.7	38.3
UPJ	1.14	1.35	87.8	10.20	10.12	19.5	3.8	48.4
WMT	1.24	3.17	64.8	14.73	14.54	14.8	5.7	36.9
Mean[c]	1.31	2.08	77.9	16.11	10.86	19.3	4.4	48.05

[a]Summary statistics for the ten most actively quoted call-option series on the CBOE and the underlying stocks over the 41-day sample period of November–December 1990. Option data are from the Berkeley Options Database, stock data are from the ISSM transaction file, and the times between trades and quotes are in minutes.
[b]Times between call trades and quotes are for trades and quotes on contracts with matched maturities and strike prices.

previous studies, midpoints of the last stock and option bid–ask quotes recorded during the interval are used as the prices for the interval, and when no quotes are available for an interval, the last recorded quotes are used. To facilitate comparisons with Chan et al. (1993), Sims (1972) style causality tests are conducted by regressing the call price change (ΔC_0) on leading and lagged stock-price changes (ΔS_i).[8]

The model estimated for each of the four interval lengths is

$$\Delta C_0 = \alpha + \sum_{i=-n}^{n} \beta_i \hat{h}_i \Delta S_i + e_i, \tag{1}$$

with $n = 3$ for the five minutes and 15 minutes series, and $n = 2$ for the hourly and daily series. The implied hedge ratio ($\hat{h}_i$) for each interval is calculated using the implied volatility that sets the dividend-adjusted American call-option model price equal to the midpoint of the call spread quoted in the preceding interval.

Analysis of the time series used to estimate (1) reveals weak negative serial correlation of the stock-quote changes and option-quote changes, and White's (1980) test reveals evidence of heteroscedasticity in the error terms. Hansen's (1982) generalized method of moments (GMM) asymptotic covariance estimator is therefore used to calculate the estimated standard errors, since it is consistent in the presence of autocorrelated and conditionally heteroscedastic residuals.[9]

Panel A of Table 2 contains the regression results for the four interval lengths. The contemporaneous and first leading stock-change coefficients (β_0, β_{-1}) are significantly positive for all four regressions, with three significant leading stock coefficients for the five-minute and 15-minute regressions. These results suggest a stock market lead of at least one day. To assess whether this apparent daily lead can be attributed to the inclusion of intervals with missing observations, the regressions are re-estimated using only observations with quotes recorded for each interval. The results are in Panel B of Table 2. The R^2's increase

[8] To assess the impact of using Sims-style tests, Granger-style tests are conducted using pre-whitened time-series for the fixed-interval regressions, but the conclusions do not differ from those obtained using the reported Sims-style tests. Furthermore, Granger-style tests require lagged values of both series, with observations recorded at the same time at each lag. Since the ordered quote-change series used in the variable-interval tests that follow fail to meet this condition, Sims-style tests are used throughout the remainder of the paper.

[9] The precise form of the covariance matrix used is the Newey-West (1987) estimator, which allows for generalized forms of autocorrelation and heteroscedasticity, without imposing any formal structure on the time series. The use of this asymptotically unbiased covariance estimator requires the choice of a truncation parameter, and since the order of the serial correlation is not known, the choice of truncation parameter is relatively ad hoc. The results are stable for various truncation parameters around the eight autocorrelation lags that are use for estimating the standard errors.

Table 2
Fixed-interval regressions[a]

$$\Delta C_0 = \alpha + \sum_{i=-n}^{n} \beta_i \hat{h}_i \Delta S_i + e_i$$

	Five-minute intervals		15-minute intervals		60-minute intervals		Daily intervals	
	Estimate	Z-stat.	Estimate	Z-stat.	Estimate	Z-stat.	Estimate	Z-stat.
Panel A: full Sample[b]								
α	0.0002	1.261	0.0005	0.869	– 0.0041	– 1.526	– 0.0434	– 13.824[c]
β_{-3}	0.0506	18.017[c]	0.0328	6.986[c]				
β_{-2}	0.0854	30.418[c]	0.0648	13.459[c]	– 0.0039	0.200	0.0085	1.991
β_{-1}	0.2271	81.170[c]	0.2247	45.342[c]	0.1990	6.571[c]	0.0248	7.162[c]
β_0	0.3344	119.841[c]	0.4953	98.590[c]	0.6804	19.820[c]	0.8742	107.443[c]
β_1	0.0221	7.955[c]	– 0.0047	– 0.957	0.0005	0.021	– 0.0149	– 5.707[c]
β_2	0.0036	1.306	0.0119	2.476[c]	– 0.0164	– 1.067	0.0046	1.641
β_3	– 0.0034	– 1.225	0.0112	– 2.358[c]				
R^2	0.1614		0.2711		0.4730		0.8403	
n	488253		128606		5998		6053	
Panel B: No missing intervals[b]								
α	0.0014	1.906	0.0009	1.096	– 0.0024	– 0.690	– 0.0539	– 14.492[c]
β_{-3}	– 0.0357	– 2.883[c]	– 0.0087	– 0.917				
β_{-2}	– 0.0102	– 0.695	– 0.0021	– 0.191	– 0.0047	– 0.265	– 0.0025	– 0.502
β_{-1}	0.0839	4.502[c]	0.0799	5.092[c]	0.1140	3.664[c]	0.0195	1.300
β_0	0.7909	40.579[c]	0.8504	54.704[c]	0.8112	21.966[c]	0.8872	92.385[c]
β_1	0.0765	4.541[c]	0.0451	4.099[c]	0.0093	0.405	– 0.0053	– 1.616
β_2	– 0.0248	– 1.871	– 0.0048	– 0.387	– 0.0181	– 1.006	0.00145	0.419
β_3	0.0215	1.630	0.0171	1.501				
R^2	0.5754		0.6464		0.6747		0.9187	
n	4200		6339		2507		2210	

[a]The sample consists of stock and call quote midpoints for ten firms from November and December 1990 (41 trading days). Three leads and lags are estimated for five and 15-minute intervals, and two leads and lags are estimated for 60-minute and daily intervals. The implied hedge ratio, $\hat{h}_j$, is estimated for the preceding interval.

[b]Observations containing intervals with missing quotes are filled using the last registered quote in panel A, and eliminated from the sample in panel B.

[c]Denotes asymptotic (Newey-West) Z statistics that are significant at the 0.01 level.

substantially, particularly where the problem of missing intervals is most severe: the five and 15 minute cases. The magnitudes of the contemporaneous coefficients also increase, and leads longer than a single interval disappear.

The only significant coefficient for the daily regression is the contemporaneous coefficient, suggesting that the daily stock-lead found with the full sample is attributable to missing observations. The three intra-day regressions suggest a stock lead of one interval, with a weaker option lead that is also one interval long. While these results are generally consistent with previous studies, they may still be attributed to asynchronous prices. After eliminating observations with missing intervals, some intervals will still contain stock quotes recorded before the option quotes for the same interval, while the opposite will be true in the remaining intervals. Asynchronous prices within one interval are likely to lead to significant estimates of coefficients for adjacent intervals, creating apparent single-period leads.

6. Variable-length interval methodology

By constructing time series of ordered quote-changes, the problems associated with the use of fixed intervals can be avoided. Referring to Fig. 1, the

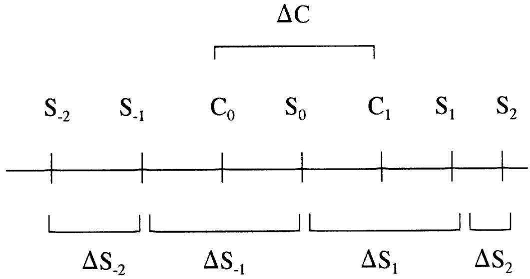

Fig. 1. Stock and option quote time sequence. The call-quote change, ΔC, is defined as $C_1 - C_0$, where C_0 is the midpoint of the option bid-ask spread quoted at time $t(C_0)$, C_1 is the midpoint of the next quote registered for the same option (i.e., the same underlying stock, strike price, and maturity) made at time $t(C_0)$, and $t(C_0) < t(C_1)$. Defining S_{-1} as the midpoint of the bid-ask spread for the underlying stock that is in effect at the time option quote C_0 is made and S_0 as the midpoint of the stock spread that is in effect at the time option quote C_1 is made, the first leading stock-price change is defined as $\Delta S_{-1} \equiv S_0 - S_{-1}$, where $S_{-1} \neq S_1$. With S_{-2} defined as the first stock-quote midpoint prior to S_{-1} with $S_{-2} \neq S_{-1}$, the second leading stock- price change is defined as $\Delta S_{-2} \equiv S_{-1} - S_{-2}$. The two stock-price changes following ΔC, ΔS_1 and ΔS_2, are defined analogously to the two leading stock-price changes (ΔS_{-2} and ΔS_{-1}): $\Delta S_1 \equiv S_1 - S_0$ and $\Delta S_2 \equiv S_2 - S_1$, where S_1 is the midpoint of the first stock quote registered after option quote C_1 for which $S_1 \neq S_0$, and S_2 is the midpoint of the first stock quote registered after S_1 for which $S_1 \neq S_2$.

option-quote change, ΔC, is defined as $C_1 - C_0$, where C_0 is the midpoint of the option bid–ask spread quoted at time $t(C_0)$, C_1 is the midpoint of the next quote for the same option made at time $t(C_1)$, and $t(C_0) < t(C_1)$. Defining S_{-1} as the midpoint of the bid-ask spread for the underlying stock that is in effect at the time option quote C_0 is made, and S_0 as the midpoint of the stock spread that is in effect at the time option quote C_1 is made, the first leading stock-quote change is $\Delta S_{-1} \equiv S_0 - S_{-1}$, where $S_{-1} \neq S_0$. With S_{-2} defined as the first stock-quote midpoint prior to S_{-1} for which $S_{-2} \neq S_{-1}$, the second leading stock-quote change is $\Delta S_{-2} \equiv S_{-1} - S_{-2}$. The two stock-quote changes following ΔC, ΔS_1 and ΔS_2, are defined analogously to the two leading stock-quote changes: $\Delta S_1 \equiv S_1 - S_0$ and $\Delta S_2 \equiv S_2 - S_1$, where S_1 is the midpoint of the first stock quote registered after option quote C_1 for which $S_1 \neq S_0$, and S_2 is the midpoint of the first stock quote registered after S_1 for which $S_1 \neq S_2$.

By construction, there are no contemporaneous stock and option-quote changes. The rare cases where a stock and option quote are registered at exactly the same second are eliminated from the sample. Also by construction, all stock-quote changes are non-zero, while zero call-quote changes are allowed. This specification facilitates tests designed to estimate lead lengths, and is motivated by the assumption that zero stock-quote changes do not contain new information. To determine whether the option market responds to the potential information contained in stock-quote changes, both zero and non-zero call-quote changes are included.

The following linear model is used:

$$\Delta C = \alpha + \beta_{-2}\hat{h}_{-2}\Delta S_{-2} + \beta_{-1}\hat{h}_{-1}\Delta S_{-1} + \beta_1\hat{h}_1\Delta S_1 + \beta_2\hat{h}_2\Delta S_2 + e, \quad (2)$$

where $\hat{h}_j$ is the implied hedge ratio, calculated using stock quote S_j.[10] Since standard tests indicate the presence of autocorrelation and heteroscedasticity, Hansen's (1982) GMM estimator is used to estimate (2).

While there is no theoretical reason to prefer option-quote changes to stock-quote changes for the dependent variable in the model, using ΔC as the dependent variable is consistent with previous studies. Furthermore, since there are multiple call options for each stock, using stock-price changes as the dependent variable increases the number of observations substantially. The conclusions are not, however, changed when stock-quote changes are regressed on leading and lagged call-quote changes.

[10] The conclusions are robust with respect to several alternative specifications of Eq. (2). The alternative specifications include regressing stock-quote changes on call-quote changes, including zero stock-quote changes, excluding non-zero call-quote changes, incorporating additional leads and lags, using historical volatilities for estimating the hedge ratios, omitting the hedge ratios entirely, and using pre-whitened series.

7. Empirical results

The hypotheses concerning the direction of the information flow between the two markets can be expressed in terms of the estimated coefficients from Eq. (2):

H_1 : Stock-quote changes reflect information first ($\beta_{-1} > 0$ and $\beta_1 = 0$).
H_2 : Option-quote changes reflect information first ($\beta_{-1} = 0$ and $\beta_1 > 0$).
H_3 : Some information is first reflected in stock-quote changes, while other information is first reflected in option-quote changes ($\beta_{-1} > 0$ and $\beta_1 > 0$).

Under the third hypothesis, the magnitudes of the coefficients can be used to determine whether there is a tendency for one market to lead the other: $\beta_{-1} > \beta_1$ implies that quotes tend to be revised first in the stock market, while $\beta_1 > \beta_{-1}$ implies that the options markets lead more often. Equal coefficients imply that, on average, information is reflected simultaneously, and neither market leads more frequently than the other.

To test these hypotheses, Eq. (2) is estimated for each of the ten underlying stocks in the sample and for a combined sample of all the securities in the data set. The full-sample results are presented in the first line of Table 3; the results for the individual stocks are consistent with the results for the full sample and are not presented. Since β_{-1} and β_1 are both significantly positive, the first two hypotheses are rejected and the third hypothesis is accepted. The coefficients and test statistics are much larger for the stock lead (β_{-1}) than for the option lead (β_1). These results imply that there is a strong tendency for the stock market to lead the options market, although at least some information is reflected in option quotes before stock quotes. The second leading and lagged coefficient estimates (β_{-2} and β_2) in Table 3 are also significantly greater than zero, although the magnitudes are smaller than those of the first leading and lagged coefficients. This implies that while traders generally react to the information reflected by a new quote in the opposite market before the next quote is made in that market, one market occasionally leads by more than a single quote change. Reaction time may be a function of the time of day or order flow, and different stocks and options may react to new information more quickly than others. By placing restrictions on the time between quotes in the two markets, the significance of the second leading and lagged coefficient estimates can be used to establish ranges for the lead times in the two markets.

The length of the maximum stock-market lead is estimated by restricting the sample to observations where the second leading stock-quote change (ΔS_{-2}) precedes the call-quote change (ΔC) by at least T minutes, for $T = 1, \dots, 7$. If T minutes are sufficient for the options market to react to the information in ΔS_{-2}, β_{-2} should not be significantly different from zero, while the first leading stock-quote change (β_{-1}) should remain positive. The regression results for the aggregate sample of ten firms are presented in Table 3. When the sample is

Table 3
Estimation of the length of the maximum stock lead[a]

$$\Delta C = \alpha + \beta_{-2}\hat{h}_{-2}\Delta S_{-2} + \beta_{-1}\hat{h}_{-1}\Delta S_{-1} + \beta_1\hat{h}_1\Delta S_1 + \beta_2\hat{h}_2\Delta S_2 + e$$

$t(C_0) - t(S_{-1})$	α	β_{-2}	β_{-1}	β_1	β_2	Adj. R^2	Obs.
Unconstrained	0.00073	0.12274	0.72050	0.17127	0.07860	0.51264	90,544
	2.410**	11.651**	97.234**	16.285**	7.411**		
> 1 min	0.00030	0.09292	0.72395	0.18196	0.05971	0.51000	51,897
	0.668	5.878**	68.190**	12.200**	4.394**		
> 2 min	0.00022	0.07823	0.73010	0.18637	0.06829	0.51350	35,372
	0.408	3.990**	50.624**	10.129**	4.241**		
> 3 min	– 0.00047	0.08574	0.72467	0.19938	0.06642	0.51281	26,367
	– 0.720	3.938**	42.448**	9.298**	3.520**		
> 4 min	0.00020	0.08510	0.72107	0.20175	0.05287	0.51343	20,543
	0.274	3.508**	33.481**	7.955**	2.632**		
> 5 min	– 0.00026	0.05735	0.73059	0.23080	0.05165	0.52621	16,655
	– 0.341	2.461**	29.345**	9.432**	2.402**		
> 6 min	0.00005	0.03647	0.73860	0.21210	0.04681	0.51228	13,921
	0.054	1.342	23.083**	7.509**	1.900		
> 7 min	0.00109	0.02546	0.73601	0.21250	0.02734	0.50263	11,716
	1.184	0.864	18.733**	6.563**	1.006		

[a]Call option bid–ask quote midpoint changes are regressed on two leading and two lagged stock-quote change variables for ten firms from November and December 1990 (41 trading days). Defining C_0 as the midpoint of the option bid–ask spread quoted at time $t(C_0)$, C_1 is the midpoint of the next quote registered for the same option at time $t(C_1)$, and S_j as the midpoint of the stock spread at time $t(S_j)$, $\Delta C \equiv C_1 - C_0$, $\Delta S_j \equiv S_j - S_{j-1}$ for $j \in \{-1, 0, 1, 2\}$, and $t(S_{-2}) < t(S_{-1}) < t(C_0) < t(S_0) < t(C_1) < t(S_1) < t(S_2)$. The implied hedge ratio estimated at time $t(S_{j-1})$ is $\hat{h}_j$. The regressions are constrained so that the call-price change (ΔC) follows the second leading stock-quote change (ΔS_{-2}) by at least T minutes for $T = 1, \dots, 7$. Asymptotic Z statistics, calculated using Newey-West standard errors, are listed below the parameter estimates. Significance at the 0.01 level is indicated by **.

restricted to observations where S_{-1} precedes C_0 by at least six minutes, β_{-2} is not significantly different from zero, while β_{-1} remains highly significant. Six minutes is a sufficient amount of time for the option quotes in the sample to reflect the information impounded in stock-quote changes, implying a maximum stock lead of six minutes.

While six minutes appears to be a sufficient amount of time for options to reflect the information impounded in stock-quote changes, options may frequently reflect information much more quickly than this upper limit. To estimate the minimum amount of time required for option quotes to adjust, observations are included in the analysis only if the first leading stock-quote change (ΔS_{-1}) precedes the call-quote change by less than T seconds, for $T = 5$, 15, 30, and 60. If the option market maker is not able to react to a stock-quote change within any one of these interval lengths, the value of β_{-1} in the corresponding filtered regression should be zero. The results of these tests appear in Table 4.

Regardless of the filter used, the coefficients of $\hat{h}_{-1}\Delta S_{-1}$ remain highly significant, and the size of the coefficients does not change materially. This suggests that, while stocks generally lead call options, this lead can be as little as five seconds. Given the institutional structure of these markets, this result is not really surprising. New stock quotes are displayed on the floor of the CBOE a few seconds after the quote is changed in New York, and option-quote reporters record the option quotes almost instantaneously. If the option quote is adjusted to reflect a change in the stock quote, the entire process, from recording the stock quote to recording the option quote, can reasonably occur within five seconds. It is of course also possible that both quotes are sometimes "simultaneously" changed in response to the same information, but at times the information is reflected in the stock quotes a few seconds before it is reflected in the option quotes.

The size and significance of the two lagged stock-change coefficients (β_1 and β_2) for the full sample imply that while information is usually reflected in stock quotes before option quotes, options occasionally lead stocks. To estimate the maximum length of the option lead, the regressions are constrained by placing a minimum limit on the time between the call-quote change (ΔC) and the following (i.e., first-lagged) stock-quote change (ΔS_1): observations are included in the estimation only if S_1 follows C_1 by at least T minutes, for $T = 1, \ldots, 7$.

The results, shown in Table 5, imply a maximum option lead of less than three minutes; when quote changes separated by more than three minutes are eliminated from the sample, the values of β_1 and β_2 are not significantly different from zero. The fact that β_1 and β_2 are generally significant when quote changes separated by less than three minutes are included in the sample suggests that option-quote changes do occasionally lead stock-quote changes. The option lead may be real in the sense that information flows from the option market to the stock market, or it may be artificial. Some information may reach both

Table 4
Estimation of length of the minimum stock lead[a]

$$\Delta C = \alpha + \beta_{-2}\hat{h}_{-2}\Delta S_{-2} + \beta_{-1}\hat{h}_{-1}\Delta S_{-1} + \beta_1\hat{h}_1\Delta S_1 + \beta_2\hat{h}_2\Delta S_2 + e$$

$t(C_1) - t(S_0)$	α	β_{-2}	β_{-1}	β_1	β_2	Adj. R^2	Obs.
Unconstrained	0.00073	0.12274	0.72050	0.17127	0.07860	0.51264	90,544
	2.410**	11.651**	97.234**	16.285**	7.411**		
< 60 s	0.00226	0.13237	0.71537	0.12674	0.07922	0.55674	49,309
	5.469**	10.852**	89.281**	10.179**	5.762**		
< 30 s	0.00294	0.13018	0.70145	0.11820	0.09567	0.54512	32,407
	5.779**	8.848**	86.744**	8.544**	7.254**		
< 15 s	0.00285	0.13514	0.69203	0.09517	0.06611	0.52290	17,789
	4.062**	6.937**	56.553**	5.480**	3.840**		
< 5 s	0.00497	0.08733	0.65060	0.03233	0.07271	0.44936	5,326
	3.535**	2.211	32.130**	0.870	2.197		

[a]Call option bid–ask quote midpoint changes are regressed on two leading and two lagged stock-quote change variables for ten firms from November and December 1990 (41 trading days). Defining C_0 as the midpoint of the option bid–ask spread quoted at time $t(C_0)$, C_1 is the midpoint of the next quote registered for the same option at time $t(C_1)$, and S_j as the midpoint of the stock spread at time $t(S_j)$, $\Delta C \equiv C_1 - C_0$, $\Delta S_j \equiv S_j - S_{j-1}$ for $j \in \{-1, 0, 1, 2\}$, and $t(S_{-2}) < t(S_{-1}) < t(C_0) < t(S_0) < t(C_1) < t(S_1) < t(S_2)$. The implied hedge ratio estimated at time $t(S_{j-1})$ is $\hat{h}_j$. The regressions are constrained so that the first leading stock-quote change (ΔS_{-1}) precedes the call price change (ΔC) by less than T seconds for $T = 5, 15, 30, 60$. Asymptotic Z statistics, calculated using Newey-West standard errors, are listed below the parameter estimates. Significance at the 0.01 level is indicated by **.

Table 5
Estimation of the length of the maximum option lead[a]

$$\Delta C = \alpha + \beta_{-2}\hat{h}_{-2}\Delta S_{-2} + \beta_{-1}\hat{h}_{-1}\Delta S_{-1} + \beta_{1}\hat{h}_{1}\Delta S_{1} + \beta_{2}\hat{h}_{2}\Delta S_{2} + e$$

$t(S_1) - t(C_1)$	α	β_{-2}	β_{-1}	β_1	β_2	Adj. R^2	Obs.
Unconstrained	0.0007	0.1227	0.7205	0.17127	0.0786	0.5126	90,544
	2.410**	11.651**	97.234**	16.285**	7.411**		
> 1 min	– 0.00028	0.11403	0.73838	0.09769	0.05408	0.5055	57,927
	– 0.681	8.605**	74.848**	7.297**	3.913**		
> 2 min	– 0.0011	0.0959	0.75355	0.0476	0.0312	0.4971	41,461
	– 2.136	6.400**	56.773**	2.858**	1.875		
> 3 min	– 0.0010	0.0971	0.7578	0.0242	0.0286	0.4828	31,806
	– 1.643	5.651**	47.471**	1.300	1.390		
> 4 min	– 0.0016	0.0832	0.7433	0.0267	0.0339	0.4597	25,211
	– 2.410**	4.404**	50.741**	1.354	1.920		
> 5 min	– 0.0022	0.0869	0.7520	0.0182	0.0277	0.4540	20,706
	– 2.931**	4.178**	45.629**	0.851	1.366		
> 6 min	– 0.0021	0.0943	0.7485	– 0.0022	0.0168	0.4427	17,399
	– 2.509**	4.024**	39.512**	– 0.099	0.742		
> 7 min	– 0.0021	0.0937	0.7479	– 0.0173	0.0116	0.4394	14,746
	– 2.255	3.710**	35.179**	– 0.702	0.477		

[a]Call option bid–ask quote midpoint changes are regressed on two leading and two lagged stock-quote change variables for ten firms from November and December 1990 (41 trading days). Defining C_0 as the midpoint of the option bid–ask spread quoted at time $t(C_0)$, C_1 is the midpoint of the next quote registered for the same option at time $t(C_1)$, and S_j as the midpoint of the stock spread at time $t(S_j)$, $\Delta C \equiv C_1 - C_0$, $\Delta S_j \equiv S_j - S_{j-1}$ for $j \in \{-1, 0, 1, 2\}$, and $t(S_{-2}) < t(S_{-1}) < t(C_0) < t(S_0) < t(C_1) < t(S_1) < t(S_2)$. The implied hedge ratio estimated at time $t(S_{j-1})$ is $\hat{h}_j$. The regressions are constrained so that the first lagged stock-quote change (ΔS_1) follows the call price change (ΔC) by at least T minutes for $T = 1, \ldots, 7$. Asymptotic Z statistics, calculated using Newey-West standard errors, are listed below the parameter estimates. Significance at the 0.01 level is indicated by **.

markets simultaneously, and the option quote may sometimes be adjusted and posted more quickly than the stock quote. While the data do not permit the identification of the source of the lead, any option lead that is present is relatively short. For the stocks in the sample, the specialists adjust the stock quotes within three minutes of the option-quote change.[11]

8. Conclusions

This study introduces a new methodology for studying lead-lag relations between stocks and options and presents new evidence concerning the flow of information between the two markets. The approach used entails the construction of real-time, variable-length intervals for price changes, as opposed to the fixed-length intervals used in previous studies. By allowing the length of the price-change intervals to vary with the frequency of trading, both the direction and length of stock and option leads can be estimated. To facilitate comparisons with previous studies and demonstrate the problems inherent in the fixed-interval approach, models with both fixed and variable-length intervals are estimated.

In the context of the conflicting results found in previous studies, the fixed-interval regression results are consistent with Chan et al. (1993) conclusion that neither the stock market nor the options market leads when five-minute intervals are constructed using bid–ask quotes. Using variable intervals reveals that leads are present, but the leads tend to be shorter than five minutes.

The variable-interval regressions show that stocks tend to lead options. The length of the stock lead can be as short as a few seconds, and is generally no longer than six minutes. Although the results indicate that most of the information flows from the stock market to the options market, option-quote changes do occasionally lead stock-quote changes by a few minutes. This suggests that, while information traders have heterogeneous market preferences, most information trading occurs in the stock market.

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[11] While the only results reported are those for the minimum and maximum stock lead and the maximum option lead, the minimum option lead length is also estimated. The minimum option lead is similar to the minimum stock lead: no more than five seconds.

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