Large Option Trades, Market Makers, and Limit Orders

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This article focuses on the difference between market makers and limit orders in their role as suppliers of liquidity. For both sources of liquidity I analyze the price behavior of stocks and options around large option trades and I estimate the premium paid by the initiator of the large trade. My findings suggest that limit orders for options are "picked off" after adverse changes in the underlying stock price. Furthermore, I find that for these transactions there is a permanent change in quotations in the direction of the transaction. After transactions where market makers supply liquidity, quotes tend to return to their pretrade level.

The trading system of many exchanges can be characterized as a mixture of an order-driven and a quote-driven market. For example, on the New York Stock Exchange (NYSE), the Chicago Board Options Exchange (CBOE), and the European Options Exchange (EOE) the best quotes in the market can come from public limit orders or from designated market makers. This article is an empirical analysis of the difference between market makers and limit orders in their role as suppliers of liquidity in a market with a mixed trading system.

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Theoretical market microstructure models generally assume that all suppliers of liquidity are flexible in adjusting bid and ask prices in response to, or in anticipation of, new information and changes in inventory positions. However, several articles discussing existing markets argue that a major problem with mixed trading systems is that they do not permit public investors to quickly adjust their limit orders when market conditions change. [See, for example, Amihud and Mendelson (1991), Black (1971), Harris (1990), and Stoll (1992)]. Because of this price inflexibility, limit orders have been described as "free trading options": a trader submitting a sell limit order provides the other market participants with a call option to buy at a fixed price, and a trader submitting a buy limit order provides the other market participants with a put option to sell at a fixed price. On some markets it might take several minutes before an instruction to cancel a limit order is executed. Book quotes therefore have "maturity" which gives them option value with respect to changes in public information.[1] For market makers the situation is different: market makers will immediately cry out new quotes if this is warranted by the arrival of new public information.

In this article I provide empirical evidence of the relevance of the price inflexibility of limit orders on the EOE. I analyze the price pattern for stocks and options around large option trades for a sample of trades where market makers provide liquidity and for a sample of trades where limit orders provide liquidity. For these samples I also estimate the liquidity premium that is received by the supplier of liquidity.

By concentrating on transactions on an options exchange I can focus on changes in the price of the underlying stock as an important source of new information that might motivate trades against limit orders for options. For example, assume that the best ask quote in the market for a certain call option comes from the limit order book. An increase in the price of the underlying stock, and consequently, an increase in the value of the call option, will reduce the liquidity premium to be paid by a prospective buyer of the option.[2] This reduction in the cost of trading might induce someone to buy the option, that is, to hit the unadjusted sell limit order. If the limit order is hit, then it is expected that the ask quote of the traded series changes

[1] In an asymmetric information model of dealer pricing, Copeland and Galai (1983) characterize the cost of supplying quotes as writing a put option (bid quote) and a call option (ask quote) to a trader with nonpublic information. Note that the "free option" description of limit orders relates to changes in public information.

[2] The liquidity premium paid by the initiator of the transaction is defined as the difference between the price at which a transaction takes place (in this example the unadjusted sell limit order) and the value of the security based on all publicly available information at that time.

permanently in the direction of the transaction. It is important to note that this change in the quote for the option is just a reflection of new public information and could be unrelated to the information content of the transaction itself.

The three variables of interest in the example above are the change in the price of the underlying stock, the change in the option quotes, and the liquidity premium. As mentioned before, I analyze and compare these variables for a sample of large option trades where market makers provide liquidity and for a sample of large option trades where the book of limit orders provides liquidity. I concentrate on large option trades because it is expected that inventory and information effects are more pronounced around these trades. Furthermore, it would be surprising to find that large limit orders in the book suffer the costly consequences of price inflexibility, because we might expect that these orders are closely monitored.

The influence of the limit order book on the price formation process has received considerable attention recently. Rock (1995) analyzes a mixed trading system where the prices of the specialist are trade-size contingent and limit prices are fixed. The specialist, who conditions his prices on order sizes, has a comparative advantage because he is able to "back away from large ominous transactions." The present article is an empirical study of the comparative advantage that market makers have because their quotes are contingent on new public information, whereas limit prices are virtually fixed for at least several minutes.[3]

Jang and Venkatesh (1991) report that actual quote revisions on the NYSE are consistent with predictions based on microstructure theories in only 25% of the cases. This finding is partly explained by the inflexibility of quotes from the limit order book. The authors stress the necessity of identifying situations where the specialist participated in the trade in validating microstructure theories (which are based on flexible quote adjustment). The results of the present article also indicate that the source of liquidity should be taken into account in empirical microstructure studies of mixed trading systems.

Harris and Hasbrouck (1992) analyze a sample of market orders and limit orders submitted to the NYSE. They show that 5 minutes after a limit order is executed, quotes have typically changed in the

[3] I refer to the time it takes on the EOE before an instruction to cancel a limit order is executed. This information is confirmed in several conversations with market makers, brokers, and EOE officials. The delay in cancellation is long compared to some other markets, such as the NYSE and the CBOE. This might aggravate the "free trading option" problem on the EOE relative to these other markets. Note however, that besides the delay in canceling the order, limit orders are relatively inflexible because monitoring and transaction costs prevent investors from continuously updating their limit orders for changes in market conditions.

direction of the trade. They attribute this finding partly to the information content of the counterparty trade, but note that it might also be due to the existence of stale limit orders. In the present article I differentiate between these two hypotheses by analyzing the price of the traded security as well as the price of the underlying stock.

Finally, Handa and Schwartz (1992) compare a strategy of trading by limit orders to a strategy of trading by market orders. They argue that one of the costs of submitting limit orders is that an adverse informational event can result in a trade at the limit price when the equilibrium value of the asset jumps past the limit price (this is referred to as bagging). Using NYSE transactions data and simulated limit order strategies they show that prices tend to bounce back toward original levels after limit order execution. Contrary to these results, I show that prices tend to change permanently in the direction of the transaction after limit order execution. Bagging, therefore, is an important motivation for many large option transactions on the EOE.[4]

This article differs from other microstructure research because I separate large option trades where market makers are the main supplier of liquidity (labeled market-maker trades) from trades where the book of limit orders is the opposite side to the initiator of the trade (labeled limit order trades). After market-maker trades I find a weak temporary effect on underlying stock prices that is consistent with inventory control by options market makers spilling over to the stock market. For limit order trades and market-maker trades there is a similar stock price pattern before large option trades. Investors tend to buy calls and sell puts after a rise in the stock price, and investors tend to sell calls and buy puts after a fall in the stock price. The stock price changes before limit orders are hit are particularly pronounced and are consistent with the view that limit orders for options are "picked off" after adverse changes in the underlying stock price. These findings are corroborated by the pattern in the option midquotes after the trade. For market-maker trades I find that quotes tend to return to their pretrade level after an initial jump in the direction of the transaction. For quotes after limit order trades, however, there is a permanent change in the direction of the transaction. I also show that the premium paid by initiators of large option trades is significantly lower for limit order trades than for similar market-maker trades.

The structure of this article is as follows. Section 1 gives a de-

[4] Biais, Hillion, and Spatt (1995) study the Paris Bourse, a computerized limit order market where liquidity is supplied by competing traders who transmit orders electronically. On the Bourse there is no relatively inflexible source of liquidity induced by market design. A theoretical analysis of the influence of private information on the price formation on a computerized limit order market without a designated market maker is provided in Glosten (1994).

scription of the market structure and the data set and discusses the selection of large option trades. Section 2 discusses the expected stock and option price behavior around large option transactions. Section 3 presents the empirical results. Section 4 concentrates on the liquidity premium paid by the initiator of the trade. Section 5 provides a summary and conclusions.

1. Description of the Market and the Data Set

1.1 Market structure

Located in Amsterdam, the EOE is a combination of a quote-driven market and an order-driven market and has a market structure similar to the CBOE. Trading takes place in an open outcry system with competing market makers on the floor of the exchange. Market makers not only compete with each other but also with orders in the limit order book. The quotes and quantities in the book are updated continuously by an order book official (OBO), and the best quotes are displayed on a screen on the floor of the exchange.[5]

In the year of my sample period, 1989, the EOE was the largest options exchange in Europe and the ninth largest in the world. The average turnover on the EOE was about 53,000 contracts per day. Prices on the EOE are quoted in Dutch guilders per share and the minimum price fluctuation is 0.10 Dutch guilders.[6] Trading on the EOE starts after the first transaction has occurred on the Amsterdam Stock Exchange (ASE).[7] As soon as the stock trades, the OBO opens the trading in the series one at a time. The opening transaction for each option series is a multilateral trade at a price at which maximum trading volume is realized.

If an investor wants to trade an option, he gives his order to a public order member (POM).[8] The POM in turn gives the order to a floor broker, who goes to the post where the option is traded and asks the

[5] An example of a floor screen is given in Appendix A.

[6] In 1989 the exchange rate was around 3.6 guilders per U.S. dollar.

[7] After the opening, trading on the ASE takes place in a continuous auction comparable to the NYSE. Central in the trading process is the hoekman, who has a similar role to the NYSE specialist. Hoekmen function as dealers, but are not allowed to deal directly with the trading public. Hoekmen also function as brokers' brokers and hold limit order books with public limit orders. The information in the limit order book is not disseminated electronically, but some information might be shared with floor brokers. Priority of execution is given to price and then time of entry. If entered into the book, the public orders have priority over other orders at the same price. There are two important differences with the NYSE. First, on the ASE each stock is assigned to at least two competing hoekmen. Second, hoekmen have no affirmative obligation to make a market.

[8] Order types on the EOE are similar to the CBOE [see Cox and Rubinstein (1985)]. Most important are market orders and limit orders. Limit orders can be day orders or good-until-canceled orders. Other orders are allowed on the EOE, but they are seldom used.

market for the series of interest. The market makers and floor brokers who are present at the post give their quotes.[9] A quote reporting terminal operator reports the new quotes and if they improve the old market quotes, the best market quotes on the floor screen change immediately.

If the floor broker asking for the quotes has a market order, or a marketable limit order, he will fill the order immediately. If he trades with a limit order in the book, then the book quotes are immediately adjusted to reflect the new situation. If the floor broker holds a limit order that cannot be filled, he may either hold the limit order and wait for a better opportunity, or book the order. In the latter case, the book will be updated and a change in the book quotes on the floor screen occurs if the limit order has a price equal to, or better than, the best quote in the book.

New best market quotes and changes in the best quotes in the limit order book are reported immediately on the floor screen. The registration of trades occurs with some delay. The time between the trade on the floor and the appearance of the trade on the floor screen ranges from 1 minute to more than 10 minutes on busy days.

1.2 Data and sample selection

The data set consists of all changes in the best quotes in the book of limit orders, all transactions, and all best bid and ask quotations in the market for options traded on the EOE in the period from 23 January 1989 to 21 April 1989. For this period I also have the prices of all transactions on the ASE in the underlying stocks.[10] The records (total number is 909,329) are time stamped to the nearest second. The data set provides me with exactly the same price information as floor traders.

The sample of large trades was created using the following criteria. First, for each underlying stock, the option trade must be among the largest 2.5% of all trades in the options on this stock in terms of the quantity traded, or in terms of the value of the trade (price times quantity).[11] Second, there cannot be another large trade (according to the first criterion) in the half hour before or after the large trade. This criterion is included so as to reduce the possibility that the

[9] Designated market makers must give a bid and ask price, and the bid-ask spread is not allowed to exceed a certain maximum that depends on the option price level.

[10] In 1989 the ASE had a market share of 71% for Dutch stocks. The price formation on competing markets for Dutch stocks (mainly the London Stock Exchange and SEAQ) is strongly dependent on the home market.

[11] Vijh (1990) studies large option trades that are equivalent to at least 250 round lots of stock. In order not to exclude smaller stocks, I prefer to use a criterion that is based on the relative size of a transaction.

observed price effect around a large transaction is contaminated by another large trade. Third, spreads and straddles are excluded. These option combinations involve two or more options, with only limited risk for the market makers. Fourth, trades in the last week before expiration are excluded to avoid any bias due to expiration-day effects [see Day and Lewis (1988)]. Finally, the large trade must be partly, or completely, executed against an order in the book of limit orders. For these trades, as is shown in Appendix B, I can determine whether the trade is seller initiated (trade at the bid) or buyer initiated (trade at the ask). Furthermore, because the reporting of changes in the book of limit orders is immediate, the exact time of these transactions can be determined.

Next, the sample is split into “market-maker trades” and “limit order trades.” Market-maker trades are trades where market makers, or floor brokers functioning as market makers, are the main source of liquidity. To be classified as a market-maker trade, less than 20% of the total quantity traded is supplied by the book. Or, alternatively, market makers acted as supplier of liquidity for more than 80% of the total quantity traded (e.g., Appendix B, Table B1). Limit order trades are large trades where the book of limit orders is the only supplier of liquidity (e.g., Appendix B, Table B2).[12]

Table 1 reports descriptive statistics for both samples. The median value of both the market maker and limit order trades is about 30,000 guilders. For the market-maker trades the median number of contracts traded is 100 and the median stock equivalent is 4,818 shares. For the limit order trades the median number of contracts traded is 80 and the median stock equivalent is 3,900 shares.

1.3 Stock price series

In Section 2, I analyze the stock price behavior around large option trades. Unfortunately, the bid-ask quotes for the underlying stock are not available. Option market makers may ask the hoekman on the ASE about his quotes. However, the main source of information for the option market makers is the last transaction price on the ASE. This price is reported immediately on the floor screen of the EOE. I use this stock price in my study.

Apart from the opening and closing prices of the underlying stock on the day of the large option trade and the opening price on the next day, I use the stock price 30, 20, 15, 10, 8, 6, 4, and 2 minutes before

[12] The third group of observations, where market-maker participation is more than 0% and less than 80%, is small ($n = 59$). For clarity of presentation, and because my focus is on the difference between market makers as the main supplier of liquidity versus the limit order book as supplier of liquidity, I do not report the results for this group.

Table 1
Descriptive statistics of the two samples

Panel A: Market-maker trades (number of observations 251)[a]

	Minimum	Maximum	Mean	Standard deviation	Median
Price of option	0.10	56.00	5.44	7.53	2.80
Number of contracts	15.00	1400.00	152.96	160.45	100
Value of trade	1000.00	602000.00	53710.52	67136.76	30000
Stock equivalent	660.00	70000.00	7292.54	7987.83	4817.70

Panel B: Limit order trades (number of observations 205)[b]

	Minimum	Maximum	Mean	Standard deviation	Median
Price of option	0.20	68.00	8.80	11.06	4.50
Number of contracts	10.00	320.00	83.87	50.80	80
Value of trade	1880.00	378000.00	44715.48	46471.70	33000
Stock equivalent	148.00	23076.90	4669.97	3288.50	3900

[a]Market-maker trades are transactions where market makers supplied liquidity for more than 80% of the total quantity traded.
[b]Limit order trades are transactions where the book of limit orders was the only supplier of liquidity.

The price of the option and the value of the trade are reported in guilders (the extreme option prices of 56 guilders and 68 guilders are for deep-in-the-money Nedlloyd options. In the beginning of 1989 there was a takeover attempt for Nedlloyd). Number of contracts refers to the number of traded option contracts. The stock equivalent is obtained by multiplying the traded number of contracts times the absolute value of the option Δ times 100, because one option contract represents rights to 100 shares of the underlying stock.

and after the large option trade. The "minus 30" stock price, S_{-30}, is the last stock price reported until 30 minutes before the large option trade. The "minus 20" stock price, S_{-20}, is the last stock price that is reported in the interval from minus 30 to minus 20 minutes before the large option trade. If there is no stock price reported during this interval, then the previous stock price is used. This procedure is repeated for all time intervals. S_0 denotes the stock price just before the large trade. Hence, S_0 is the last stock price reported in the interval from 2 minutes before the time of the large option trade to just before the time of the trade (or the previous stock price if there is no stock price reported).

2. Hypotheses About the Price Behavior of Stocks and Options Around Large Option Trades

The following discussion relates the expected price behavior around large option trades to the option-like characteristic of quotes, to inventory control by suppliers of liquidity, and to the signal given by the large option transaction.

Market makers can quickly adjust their quotes in response to new public information by giving new quotes. For public investors, however, it might take several minutes before an instruction to cancel a limit order is executed. Therefore, book quotes, contrary to market-maker quotes, have option value with respect to changes in public information. According to this "option" hypothesis, sell (buy) limit orders for call (put) options are more likely to be executed after an increase in the price of the underlying stock, and buy (sell) limit orders for call (put) options are more likely to be executed after a decrease in the underlying stock price. Furthermore, according to the option hypothesis, the quotations for the traded series will change permanently in the direction of the transaction as the new public information is reflected in the quotes.

Inventory control models predict that a large option trade is followed by a temporary change in the quotes of the traded series in the direction of the trade [see Ho and Stoll (1983)]. The expected change in the price of the underlying stock depends on the change in the exposure of the portfolio of the market maker to changes in the stock price (his Δ position).[13] After a large option transaction which decreases the Δ position of a supplier of liquidity, inventory control can result in an increased demand for the underlying stock. The Δ position of a market maker decreases if he sells call options or buys put options. After Δ increasing trades, an increase in the supply of the underlying stock could result. Price effects due to inventory control are expected to be temporary and are expected to be stronger the larger the equivalent amount of stock for which suppliers of liquidity participated in the transaction. It is important to note that active inventory control after large transactions is more relevant for market makers than for limit order traders. In general, market makers try to return to a Δ-neutral position after supplying liquidity, whereas limit order traders primarily supply liquidity in order to implement their investment decisions.

Several authors have argued that it is attractive for traders with superior information about the future stock price to exploit their information on the options market. [See, for example, Bhattacharya (1987), Black (1975), and Stephan and Whaley (1989)]. Accordingly, large option trades might give signals and result in permanent changes in the stock and option prices. More specifically, I expect that buyer-initiated trades in calls (puts) and seller-initiated trades in puts (calls) are accompanied by permanent stock price increases (decreases) because

[13] Although the value of their portfolio is exposed to several risks such as changes in interest rates and time to maturity, market makers are primarily concerned about the Δ of their portfolio. Jameson and Wilhelm (1992) study the inventory control problem of an options market maker.

of the signal given by the option trade. For the traded option series a permanent change in the direction of the transaction is predicted. Furthermore, because short-term out-of-the-money options and short-term at-the-money options have a high leverage factor relative to the other option series on the same underlying stock, the signal is expected to be stronger for trades in these options than for the other option series.

3. Empirical Results on Price Behavior Around Large Option Trades

3.1 Stock price behavior around large option trades

In this section I report and compare stock price patterns around the market-maker trades and the limit order trades. S_{j0} is the price of the underlying stock at the time of large option trade j and S_{jt} is the price of the stock at time t relative to the time of the large option trade. The stock price difference between time t and time 0 is defined as

$$e_{jt} = S_{jt} - S_{j0} \tag{1}$$

For the sample of market-maker trades and limit order trades the results are reported in Figure 1. Buyer-initiated call trades and seller-initiated put trades are grouped together, as the hypotheses specified in the previous section predict similar stock price reactions for both groups. For the same reason, seller-initiated call trades and buyer-initiated put trades are grouped together.

The results yield several interesting insights. First, for both market-maker and limit order trades there is a systematic stock price pattern before large option trades. Investors tend to buy calls and sell puts after a rise in the stock price, and investors tend to sell calls and buy puts after a fall in the stock price. Despite the similarity in sign, the hypothesis that the median stock price difference for the market-maker trades equals the median stock price difference for the limit order trades is rejected at the 1% level for all $t < 0$ (not reported). The hypothesis of similar medians for market-maker trades and limit order trades is not rejected for all $t > 0$ (not reported).

Second, on average the stock price increases by 8.2 cents in the last 2 minutes before sell (buy) limit orders for call (put) options are hit. For market-maker trades this increase is 1.7 cents. The average fall in stock price in the last 2 minutes before buy (sell) limit orders for call (put) options are hit is 5.2 cents. For market-maker trades the average fall is 1.4 cents.[14] For the sample of limit order trades I find that in

[14] Although the size of the stock price changes before market-maker trades is smaller, the sign is

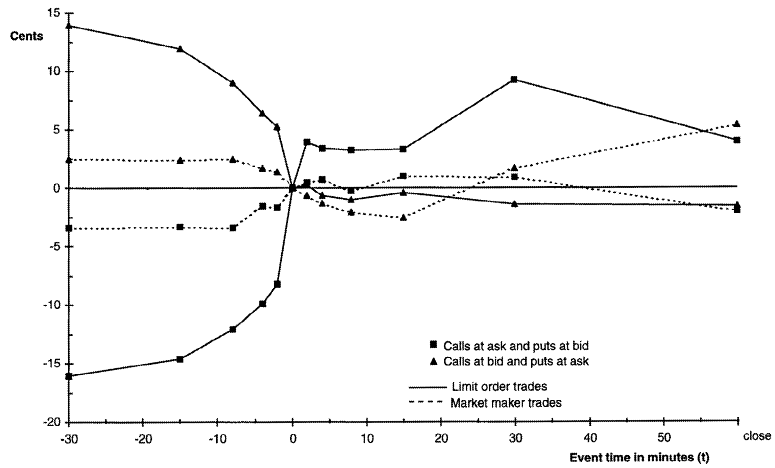

Figure 1
Stock price differences around large option transactions
For each option trade the stock price difference for each t is calculated as $S_{jt} - S_{j0}$. S_{j0} is the stock price at the time of the trade ($t = 0$), and S_{jt} is the stock price at time t relative to the time of the trade, where t is measured in minutes. The average stock price differences reported in the figure are in cents. Market-maker trades are transactions where market makers supplied liquidity for more than 80% of the total quantity traded. The sample size is 124 for calls traded at the ask and puts traded at the bid, and 127 for calls traded at the bid and puts traded at the ask. Limit order trades are transactions where the book of limit orders was the only supplier of liquidity. The sample size is 101 for calls traded at the ask and puts traded at the bid, and 104 for calls traded at the bid and puts traded at the ask.

the last 2 minutes before the transaction, the stock price moved in the direction predicted by the option hypothesis in 40% of the cases, and in the opposite direction in 5% of the cases. For the sample of market-maker trades these numbers are 11% and 5%, respectively.[15]

Third, the stock price changes after large market-maker trades provide only weak support to the idea that inventory control of option market makers after large option transactions influences the stock price. Although most stock price changes are in the direction predicted by the inventory control hypothesis, for more than 50% of the observations a change in the stock price did not occur in the 8 minutes following the trade. Furthermore, the influence of the large option trades is small. After 15 minutes, the mean effect is 1.0 cent for calls

similar to limit order trades. As pointed out by the referee, this might indicate that market makers sometimes fail to react to movements in the stock price. In the next section I provide further evidence on this issue.

[15] Detailed descriptive statistics are available from the author.

traded at the ask and puts traded at the bid, and 2.5 cents for calls traded at the bid and puts traded at the ask.[16]

Finally, for both samples the null hypothesis that a stock price increase after a large option transaction is as likely as a stock price decrease is not rejected using the closing prices on the day of the large trade. For the sample of market-maker trades the stock price changed in the direction predicted by the asymmetric information hypothesis in 43% of the cases and in the opposite direction in 42% of the cases. For the sample of limit order trades these numbers are 39% and 45%, respectively. This result, that large option trades are not informative about future stock prices, is consistent with the findings of Vijh (1990).[17,18]

3.2 Option price behavior around large option trades

The foregoing section shows that the stock price pattern before limit order trades has the same sign as the stock price pattern before market-maker trades, but is more pronounced. To further analyze the competing hypotheses, the option quotations of the traded series surrounding the large trades are studied in this section.

As discussed earlier, the inventory control hypothesis and the option hypothesis predict a different posttrade pattern in the quotations of the traded option series. According to the inventory control hypothesis, option quotations will change temporarily in the direction of the trade. After an initial change the quotes are expected to return toward their pretrade level. Note that a quote reversal will also be observed if a new limit order is placed between the pretrade quote and the transaction price after a trade has been (partly) executed against a quote in the limit order book. I cannot distinguish between these hypotheses and will henceforth refer to the quote reversal hypothesis instead of the inventory control hypothesis.

According to the option hypothesis, permanent changes of the quotations in the direction of the trade will occur. After the initial change the quotes are expected to stay at their new level. The quotes are

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[16] I split both samples into categories (small, medium, and large) according to the stock equivalent of the market-maker participation in the trade. I did not find stronger stock price effects for larger option trades.

[17] In a stronger test I separated the short-term out-of-the-money and short-term at-the-money options, and the other option trades. Consistent with the theoretical results in Biais and Hillion (1994), separate analysis of both groups did not provide any evidence of an information effect. Using the opening prices on the day after the trade, I found the same result.

[18] There is more than one transaction in an option on the same underlying stock on the same trading day for 20 market-maker trades and 10 limit order trades. Exclusion of these observations does not lead to a different conclusion.

expected to change even further in the direction of the trade if the initial quote adjustment only partially reflects the new information.

I use the Page (1963) test for ordered alternatives to test these hypotheses.[19] The change in the midquote is defined as

$$\Delta M_{ji} = 0.5Q(A_{ji} + B_{ji} - A_{j0} - B_{j0}), \tag{2}$$

where $A_{j0}(B_{j0})$ is the last ask (bid) quote for option series j before the large transaction in option series j; $A_{ji}(B_{ji})$ is the ith ask (bid) quote for option series j relative to the last quote before the large transaction in option series j (for example, A_{j1} denotes the first ask quote for option series j after the transaction); and Q is $+1$ if the transaction was at the ask and -1 if the transaction was at the bid.

To test the quote reversal hypothesis for the sample of market-maker trades, I use the first n quotations after the transaction. For each market-maker trade these quotations are ranked according to ΔM_{ji}. Rank number 1 is given to the observation with the smallest change in the midquote, rank number 2 is given to the second smallest change in midquote, etc. Then, n groups are formed with the 1st, 2nd, ..., and nth quotations, respectively. The null hypothesis is that quotes do not revert after a transaction and therefore the average rank is expected to be the same among the groups, H_0: $v_1 = v_2 = \cdots = v_n$, where v_i is the average rank of all ith quotations. The quote reversal hypothesis predicts that the rank decreases across groups 1 to n, where at least one of the following inequalities is strict, H_a: $v_1 \geq v_2 \geq \cdots \geq v_n$.

The option hypothesis, which applies to limit order trades, predicts that the quotations after a transaction change permanently in the direction of the transaction. If the initial quote adjustment only partially reflects the new information, then the average rank increases across groups 1 to n. The null hypothesis for the limit order trades is H_0: $v_1 = v_2 = \cdots = v_n$ and the alternative hypothesis is H_a: $v_1 \leq v_2 \leq \cdots \leq v_n$.

In the empirical tests, I use the first and last quotation of the traded series on the day of the large transaction and the quotes in the first 30 minutes surrounding the large option trade.[20] Table 2, panel A gives the midquote changes around market-maker trades. Panel B gives the midquote changes around limit order trades.

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[19] The Page test for ordered alternatives tests the hypothesis that the median of a number of k matched samples is the same versus the alternative that the medians are ordered in a specific sequence.

[20] I have selected large option trades with no other large option trade on the same underlying stock in the 30 minutes before or after the transaction in order to reduce the possibility of a contaminating price effect of another large option trade (see Section 1.2). For the same reason I use the 30 minutes window in this section.

Table 2
Midquote changes in the traded option series around large option trades

Panel A: Average midquote changes around market maker trades

Quote	Open	−5	−4	−3	−2	−1	0	1	2	3	4	5	Close	z
$S \geq 5$	−4.5	2.3	−2.3	−1.3	−1.0	0.2	0	12.1	9.8	11.0	11.0	6.9	−0.4	3.1**
$n = 60$	(47.7)	(21.3)	(21.8)	(19.1)	(14.5)	(11.0)		(9.8)	(13.6)	(14.8)	(16.7)	(15.0)	(34.0)	
$S \geq 4$	−4.5		−3.5	−1.0	−0.8	−0.2	0	11.6	9.7	10.4	9.9		−1.4	2.2*
$n = 90$	(42.1)		(20.8)	(18.8)	(15.8)	(13.6)		(10.1)	(13.8)	(14.6)	(16.5)		(97.8)	
$S \geq 3$	10.5			0.6	0.9	1.1	0	13.3	12.9	12.9			5.1	2.9**
$n = 133$	(143.2)			(24.9)	(21.7)	(16.3)		(13.3)	(26.1)	(29.0)			(40.1)	
$S \geq 2$	6.4				0.0	0.3	0	12.9	11.7				5.5	4.1**
$n = 183$	(126.6)				(19.4)	(14.9)		(13.7)	(23.3)				(35.2)	
$S \geq 1$	7.3					0.3	0	13.2					7.6	5.3**
$n = 219$	(116.5)					(15.3)		(13.9)					(34.7)	

Table 2
continued

Panel B: Average midquote changes around limit order trades

Quote	Open	−5	−4	−3	−2	−1	0	1	2	3	4	5	Close	z
$S \geq 5$	−6.5	10.2	1.5	4.8	6.5	−3.1	0	15.9	21.0	21.5	23.2	29.8	30.9	2.0*
$n = 33$	(111.2)	(25.3)	(18.0)	(15.6)	(18.9)	(17.7)		(14.2)	(25.2)	(32.4)	(27.5)	(39.6)	(124.5)	
$S \geq 4$	−1.4		−1.8	2.6	4.3	−2.7	0	15.5	18.8	20.4	20.7		22.5	1.3
$n = 53$	(97.8)		(23.4)	(17.5)	(17.4)	(15.6)		(13.6)	(21.6)	(29.8)	(27.9)		(100.5)	
$S \geq 3$	4.8			7.4	7.9	1.7	0	16.4	19.3	24.0			29.3	1.9*
$n = 86$	(83.1)			(27.8)	(20.2)	(18.0)		(14.5)	(22.0)	(29.7)			(82.8)	
$S \geq 2$	5.2				5.6	0.9	0	17.7	22.5				30.3	2.0*
$n = 137$	(77.0)				(21.9)	(18.9)		(16.9)	(30.2)				(81.9)	
$S \geq 1$	5.6					1.9	0	17.8					27.7	2.6**
$n = 181$	(69.0)					(18.3)		(17.0)					(71.8)	

Quote denotes event time. Quote = 0 refers to the last quotation before the large transaction occurred and quote = −1 (+1) to the preceding (following) quotation. For buyer-initiated trades the change in the midquote is defined as the difference between the *i*th midquote and the midquote based on the last quotes before the large transaction occurred (quote 0). For seller-initiated trades the change in the midquote is defined as the difference between the midquote based on the last quotes before the large transaction occurred and *i*th midquote. The reported average midquote changes are in cents. S is the minimum number of quotations in the first 30 minutes after a transaction in order to be included in the sample. The number of observations (n) decreases as S increases, because for each S, I only use transactions followed by S or more quotations in the first 30 minutes after the transaction. The z-statistic is based on the Page test for ordered alternatives for $S \geq 2, 3, 4$, and 5 and on the Wilcoxon rank test for $S \geq 1$. Since the alternative hypothesis specifies an ordered hypothesis, the tests are one-tailed. An * (**) indicates that the result is significant at the 5% (1%) level. Standard deviations are in parentheses.

The first line in both panels in Table 2 gives the result for transactions with at least five quotations in the first 30 minutes after the transaction. The following discussion first concentrates on these transactions. The other lines in the table give the results for transactions with at least four, three, two, and one quotations in the 30 minutes after the transaction. For both samples the midquotes do not change much prior to the transaction.

For the market-maker trades there is an average price jump in the direction of the transaction of 12.1 cents immediately after the trade. After the initial price jump the midquote falls back to its pretrade level. The decline is significant at the 1% level as indicated by the z-statistic based on the Page test. It is interesting to note that the pattern in option midquotes around large trades is similar to stock market research where, consistent with dealer pricing to stabilize inventory, a negative serial dependence in midquote returns is reported [for example, Huang and Stoll (1994)]. However, as discussed before, one should be cautious in attributing the return of the midquote to the pretrade level to inventory control, as it could also be explained by new limit orders being placed between the pretrade midquote and the transaction price after the transaction. Finally, it should be noted that the option midquote behavior following market-maker trades is inconsistent with the view that the systematic stock price pattern preceding these transactions indicates that options market makers are too slow in adjusting their quotes to changes in the underlying stock price. If this was the case, a permanent change in the option midquote in the direction of the trade would have been observed.

For the sample of limit order trades there is an average change in the midquote in the direction of the transaction of 15.9 cents immediately after the transaction. After this initial jump the midquote rises even further. The price increase after the initial price jump is significant at the 5% level. Note that the option price pattern after the trade is consistent with both asymmetric information models of dealer pricing and the description of limit orders as free trading options. The evidence on the price behavior of the underlying stock after limit order trades, however, supports the latter explanation. Furthermore, consistent with the option description, limit orders for options are hit after adverse changes in the underlying stock price.

The results for transactions with at least four, three, two, and one quotations in the 30 minutes after the transaction also show that after market-maker trades quotes tend to return to the pretrade level, and that after limit order trades quotes tend to change permanently in the direction of the transaction. The difference in the price pattern for the two samples clearly shows that the source of liquidity should be taken into account in empirical microstructure studies.

4. The Premium Paid by the Initiator of a Large Trade

The findings reported in the previous section support the idea that some trades against the limit order book are motivated by "mispricing" of the limit order after new public information arrives on the market. This section tests two implications for the premium that is paid by the initiator of the large trade.

Because of the comparative advantage of market makers to adjust prices to new public information, I expect that the premium paid in market-maker trades is higher than the premium paid in similar limit order trades. To test this hypothesis I compare the liquidity premium for a sample of market-maker trades and limit order trades that are matched based on the underlying stock and the size of the transaction.

The second hypothesis focuses on the relation between the liquidity premium and trading activity. Since stock price changes are public information, I hypothesize that the extent to which a limit order can be mispriced (i.e., the limit order gets a liquidity premium that is low or even negative) is limited by competition among traders. This competition is expected to be stronger the greater the trading activity in options on the underlying stock. I therefore predict a positive correlation between the premium paid by the initiator of a limit order trade and the activity on the trading floor in options on the underlying stock. For the sample of market-maker trades I expect a negative correlation between the liquidity premium and trading activity, consistent with the inventory control and asymmetric information models of dealer behavior. [See, for example, Easley and O'Hara (1987) and Ho and Stoll (1983)].

The liquidity premium paid by the initiator of the transaction is defined as the difference between the price at which a transaction takes place and the value of the security based on all publicly available information at that time. I calculate the liquidity premium as

$$p = \begin{cases} \text{calculated option price} - \text{bid, for trades at the bid} \\ \text{ask} - \text{calculated option price, for trades at the ask,} \end{cases} \tag{3}$$

where bid (ask) is the price at which the option trade occurred and calculated option price is the model price at the time of the trade using the binomial model.[21]

To calculate the option price I take dividend payments and the American character of the traded options into account. The interest

[21] The use of the Cox, Ross, and Rubinstein (1979) model, which is based on perfect market assumptions, may be justified by the fact that almost all option market participants make use of this, or similar, option pricing models. For an option pricing model in a market with transaction costs see, for example, Boyle and Vorst (1992).

rate is the 3-month rate on Dutch T-bills. I use two volatility measures. The first measure is the average of the volatility implied by the end-of-the-day prices of the most traded short-term, medium-term, and long-term option series written on the same underlying stock.[22] The second measure is the volatility implied by the end-of-day price of the most traded option series written on the same underlying stock with the same time to maturity as the traded option series.[23] The other input variables are the time to maturity, the exercise price, and the price of the underlying stock at the time of the large trade.

The first row in Table 3, panel A (panel B) provides some descriptive statistics of the realized premiums for the limit order trades using the first (second) volatility measure. The second row in Table 3, panel A (panel B) provides descriptive statistics of the realized premiums for the market-maker trades using the first (second) volatility measure. Since the results in both panels are almost identical, I only discuss the results in panel A.

From the first row in Table 3, panel A we see that in more than 60% of the cases the liquidity premium received by the limit order trader is negative; the trade occurred at the expense of the limit order trader. The average loss for the limit order trader is 7 cents per traded contract. The median loss is 5 cents per contract. For market-maker trades the average liquidity premium is 4 cents per traded contract, and the median premium is 5 cents per contract. Furthermore, 60% of the market-maker trades have a positive premium.

To compare the liquidity premium paid in limit order trades and similar market-maker trades, I matched trades from both samples in options on the same underlying stock, with the criterion that the difference in the number of traded contracts was smaller than 20%.[24] This yielded 100 pairs of transactions. For the matched transactions, the average liquidity premium is 7 cents larger for the market-maker trades than for the limit order trades. I used the Wilcoxon test for two matched samples to test whether the median in the market-maker trades equals the median in the limit order trades. The z-value based on this test equals 5.25, which indicates that the liquidity premium in market-maker trades is significantly (at the 1% level) higher than the

[22] I use the option series with the highest turnover in order to minimize the problem of nonsynchronous data. If one of the implied volatilities could not be calculated, then I used the average of the two remaining implied volatilities. I excluded very long-term options (time to maturity in excess of 9 months) because of systematic and large differences between the model prices and the observed prices.

[23] For 15 limit order trades and 16 market-maker trades the implied volatility could not be calculated because the end-of-day price of the options with the same time to maturity as the traded option series exceeded its theoretical boundary [see Bhattacharya (1983)].

[24] Matching of trades based on the equivalent number of stocks gives similar results.

Table 3
Liquidity premium paid by initiators of large option trades

Panel A: Liquidity premium paid by initiators of large option trades using the average implied volatility[a]

	Mean	STD	Minimum	Maximum	Median	< 0	0	> 0
Limit order trades	−0.07	.61	−2.69	3.61	−.05	103	2	62
Market maker trades	0.04	.62	−2.46	6.05	.05	85	4	132

Panel B: Liquidity premium paid by initiators of large option trades using the implied volatility of the most traded option series with the same time to maturity[b]

	Mean	STD	Minimum	Maximum	Median	< 0	0	> 0
Limit order trades	−0.05	.60	−1.97	5.79	−.05	93	5	54
Market maker trades	0.05	.60	−1.70	7.11	.05	70	4	131

[a]Average volatility implied by the closing prices of the short term, medium term, and long term option series with the largest trading volume and written on the same stock as the traded option.
[b]Volatility implied by the closing price of the most traded option series with the same time to maturity as the traded option series and written on the same stock.

The liquidity premium is defined as the calculated option price minus the transaction price in case of a trade at the bid, and the liquidity premium is defined as the transaction price minus the calculated option price in case of a trade at the ask. The reported premium is in guilders. Mean denotes the average premium, STD the standard deviation, and < 0, 0, and > 0 indicates the number of observations with negative, zero, and positive liquidity premiums. Very long-term options (time to maturity longer than 9 months) are excluded because of the systematic and large difference between model prices and market prices. The large minimum and maximum are in all cases for options on Nedlloyd. If I exclude Nedlloyd the maximum premium for the limit order trades is 0.74 (1.00 in panel B) and for the market-maker trades is 1.07 (0.98 in panel B). The minimum for the limit order trades is −1.02 (−0.94 in panel B) and for the market-maker trades is −0.71 (−1.03 in panel B.)

liquidity premium in similar limit order trades. The same conclusion is reached when the second volatility measure is used (z-value = 5.28).

The second hypothesis stated at the start of this section is that as more traders are active in options on a stock, arbitrage opportunities will be recognized sooner and the loss for the limit order trader will be smaller. Therefore, a positive correlation between the liquidity premium and turnover is expected for limit order trades. For the market-maker trades we expect a negative correlation between the liquidity premium and turnover. To test these hypotheses, the underlying stocks are ranked according to the total turnover in stock options on the EOE in the sample period and related to the premium for trades in options on these stocks. The rank number (1 for the lowest turnover, 2 for the next lowest, etc.) is used as a proxy for the number of traders active in the options written on a particular stock.

For each underlying stock, Table 4 reports the turnover in stock options in the sample period, the average premium for trades in options on each of the stocks, the signs of the premiums, and the cumulative number of negative premiums relative to the cumulative total number of observations. Panel A gives the results for market-maker trades and panel B gives the results for limit order trades.[25]

The results in Table 4, panel A indicate that there is no relation between the premium received by market makers and the turnover on the options exchange. The Spearman rank correlation coefficient between the activity proxy and the premium per contract paid by the initiator of the trade equals −0.01. Although the sign is as expected, the result is not statistically significant.

Table 4, panel B gives the results for the limit order trades. The last column, the cumulative number of trades with a negative liquidity premium divided by the cumulative total number of observations, suggests a positive correlation between the premium received by the limit order trader and the turnover on the option exchange. Indeed, the Spearman rank correlation between the activity proxy and the premium per contract paid by the initiator of the trade in case of limit order trades is +0.24 (significant at the 1% level). This result is consistent with the hypothesis formulated above and provides further support to the idea that the motive to initiate a trade against large limit orders in the book is to exercise the option given to the market by limit order traders as soon as this option gets in the money.

5. Summary and Conclusions

This article concentrates on the difference between market makers and the limit order book in their role as suppliers of liquidity on the EOE. For both sources of liquidity I analyze the stock and option price behavior around large options trades, and I estimate the premium that is paid by initiators of large option trades.

I use limit order book data to determine the time of a trade, the sign of a trade (sale or purchase), and the liquidity market makers and the limit order book supply in a trade. Based on the expected difference in price behavior, the sample is split in trades where market makers are the main supplier of liquidity (market maker trades) and trades where the limit order book is the opposite side to the initiator of a large trade (limit order trades).

After market-maker trades I find a weak temporary effect on the stock price that is consistent with inventory control by option market makers spilling over to the stock exchange. For both samples I find no permanent effect on the stock price after large option trades, providing evidence against the hypothesis that these trades are based

[25] In Table 4 the average implied volatility is used. The results using the implied volatility of the most traded option series with the same time to maturity as the traded option lead to the same conclusions.

Table 4
Relation between the turnover on the options exchange and the liquidity premium paid by the initiator of the transaction

			Panel A: Market-maker trades					Panel B: Limit order trades				
Rank	Ticker symbol	Options turnover	Average premium	Sign < 0	Sign 0	Sign > 0	Percent	Average premium	Sign < 0	Sign 0	Sign > 0	Percent
1	ROB	2694	0.16			1	0					
2	WES	11974	0.18			2	0	−0.62	2		0	100
3	HEI	20686	0.29	2		2	28	−0.31	6		1	89
4	AH	21246					28	0.19	1		1	82
5	ELS	24310	−0.05	3		2	42	−0.10	7		1	84
6	AGN	32917	0.06	2		3	41	0.17	0		1	80
7	BT	38340	0.02	6	1	10	38	−0.21	7		0	85
8	ARB	45262	0.15	1		5	35	−0.21	9		3	82
9	AMV	46278	−0.31	4		4	38	−0.17	3		3	78
10	VOC	55835	−0.07	4		4	39	−0.21	6		1	79
11	GIS	66698	0.01	6		7	40	−0.28	4		2	78
12	NED	69439	0.25	5		3	43	0.08	5		6	73
13	ABN	95995	−0.01	11		10	45	−0.11	7		2	73
14	NN	99957	0.08	5		11	43	0.03	7		6	70
15	KNP	113980	−0.03	6	1	6	43	−0.05	10	1	6	69
16	KLM	139088	0.06	6		10	43	0.01	5	1	3	68
17	UNI	180603	−0.07	8	1	9	43	0.13	7		11	64
18	AKZ	183963	0.16	6		14	42	0.01	5		4	63
19	PHI	333755	0.07	5		15	40	−0.02	7		5	63
20	RD	451379	0.09	5	1	14	39	−0.12	5		6	62

The rank number is based on the turnover on the EOE in the first 3 months of 1989, which is reported in the third column (Source: Rokin 65, Optiebeurs, 1989-2). Average premium refers to the premium received by the supplier of liquidity averaged over all trades for options on a particular stock. The premium is defined as the calculated option price minus the transaction price in case of a trade at the bid, and as the transaction price minus the calculated option price in case of a trade at the ask. The option price is calculated using the average volatility implied by the closing prices of the short-term, medium-term, and long-term option series with the largest trading volume and written on the same stock as the traded option. Sign < 0, 0, and > 0 indicates the number of observations with negative, zero, and positive premiums, respectively. Percent in the table is calculated as the cumulative number of trades with a negative premium divided by the cumulative number of trades times 100%.

on private information. For both limit order and market- maker trades there is a systematic stock price pattern before large option trades. Investors tend to buy calls and sell puts after a rise in the stock price and investors tend to sell calls and buy puts after a fall in the stock price. The stock price changes before limit orders are hit are particularly pronounced and are consistent with the idea that limit orders for options are "picked off" after adverse changes in the underlying stock price.[26] To further investigate this, the midquote behavior of the traded option series before and after the large trade is analyzed. It has been shown that quotes after market-maker trades tend to return to their pretrade level. For quotes after limit order trades, however, there is a permanent change in the direction of the transaction.

I also estimate the premium paid by initiators of large option trades. It is shown that this premium is significantly lower for limit order trades than for similar market-maker trades. Furthermore, it is shown that for the sample of transactions where the limit order book is the only supplier of liquidity, the premium paid by the initiator of the transaction is negative on average. Finally, I test the hypothesis that competition limits the value of the option that is given to the market by a trader who submits a limit order. The significant positive correlation between the liquidity premium paid by the initiator of the trade and trading activity is consistent with this hypothesis.

Appendix A: Information on the Floor Screen

For every optioned stock on the EOE there is a screen for both call and put options giving information about the quotes, prices, and volume for the option series, and prices of the underlying stock. There are no hidden orders, and only the best quotes in the market and in the limit order book are shown on the screen. Table A-1 gives an example for call options on Royal Dutch.

The first column gives all available call option series. The calls with the shortest time to maturity and the lowest exercise price are at the top of the screen. The second column gives the closing prices of the previous day. The third column reports the last price at which trading took place. The next four columns give information about the best prices (bid and ask) in the book of limit orders and the accompanying sizes. For each option series the book, which is held by the OBO, is

[26] These results point at a potential problem in empirical microstructure studies where the source of liquidity is not taken into account. For example, our results for limit order trades indicate that the stock market leads the option market. This finding is explained by the existence of stale limit orders in the option market and not by a preference of informed traders to trade on the stock market.

Table A-1
Price/volume information on class display

	Close	Last	B-bid	B-ask	B-size	A-size	M-bid	M-ask
Apr 120	26.5						24.0	26.0
Apr 125	22.0						19.0	21.0
Apr 130	16.0		15.5	22.0	13	1	15.5	16.5
Apr 135	12.0	12.0	11.5	18.0	1	2	11.5	12.0
Apr 140	8.0	8.0	6.0	8.0	1	4	7.5	8.0
Apr 145	5.0	4.6	4.5	5.0	2	9	4.5	5.0
Apr 150	2.5	2.3	2.2	2.4	3	5	2.2	2.4
Apr 160	0.8	0.7	0.6	0.8	4	6	0.6	0.8
Jul								
Oct								
Stock RD	Close	Open	High	Low	Last		Time	
	144.4	144.7	144.7	143.7	144.0		15.00.03	

a collection of buy and sell limit orders, ordered by price. Priority of execution is given to price and then time of entry (irrespective of the size of the limit order). If entered into the book the order has priority over all other orders at the same price. The OBO's terminal operator continuously updates the book as new limit orders are entered into the book or limit orders in the book are hit or withdrawn. Note that the size reported on the screen is the aggregate number of contracts of all limit orders at the best quotes. The last two columns on the screen give the best quotes in the market. Note that for the April 145, 150, and 160 series, the best quotes in the market are the same as the best quotes in the book. The last row gives information about the underlying value.

Appendix B: The Time of Trading and the Buy/Sell Classification

Limit order book data were used to determine the time at which a trade took place and to classify a transaction as a trade at the ask or a trade at the bid. The database consists of four data sets which provide (1) the best bid and ask quotations in the market of all traded option series (number of records = 399,206); (2) all transactions in these option series (number of records = 167,646); (3) all changes in the best quotes (price and quantity) in the book of limit orders of these series (number of records = 341,777); and (4) the transaction prices of the underlying stocks (number of records = 39,061).

Combining these data sets in chronological order gives the trade history of an option series. Table B-1 reports the history of a middle-term, at-the-money Unilever call option on a day in March 1989. The asterisk (*) mark in the table is inferred by the author and does not appear on the EOE tape.

The $*$ in the Time column marks the moment that a transaction at a

Table B-1
Unilever/call/K = 13,000/T = 89.07.21

Time	Market		Book		Quantity Book		Option trade		Stock Price
	Bid	Ask	Bid	Ask	Bid	Ask	Price	Quantity	
12.08.06	430	500							13,050
12.20.50							480	2	13,050
12.22.03	430	490	430	490	2	10			13,050
12.29.50	430	470	430	470	2	2			13,050
13.10.58*			420	470	5	2			13,050
13.11.00	420	470							13,050
13.15.53							430	160	13,050
13.58.49	430	470	430	470	10	2			13,060
14.15.06	440	470							13,060
14.18.52	440	460	430	460	10	10			13,060
14.29.38							440	15	13,060
14.38.49	440	460	440	460	5	10			13,060

Table B-2
VOC/call/K = 4,000/T = 89.10.21

Time	Market		Book		Quantity Book		Option trade		Stock Price
	Bid	Ask	Bid	Ask	Bid	Ask	Price	Quantity	
10.53.12			580	680	10	5			4,460
10.55.54			580	680	10	105			4,470
11.26.38	600	650	580	650	10	5			4,470
11.34.39*			580	680	10	105			4,520
11.35.02	600	680							4,520
11.35.17	620	680							4,520
11.42.10							650	5	4,520
11.50.44*			580	700	10	5			4,550
11.50.57	650	680							4,550
11.51.00	650	700							4,550
11.54.34							680	105	4,550
11.55.04	650	700							4,550
12.52.31			670	700	1	5			4,550

price of 430 occurred that included an order in the limit order book. I base this conclusion on the widening of the spread in the limit order book at 13.10.58 which indicates that a limit order was hit.[27] On the EOE, orders that are divided among several market makers and/or the limit order book are reported as one trade. In the transaction data set there is only one trade reported within a reasonable time (I used 30 minutes) at 430.[28] This trade is reported at 13.15.53 (P = 430, Q = 160). From the data I infer that the trade that is reported at 13.15.53,

[27] The data set does not indicate if the book spread widens because a limit order is hit or because a limit order is canceled. It is therefore possible that the $*$ marks the moment that a limit order is canceled. However, according to EOE officials, it is very likely that a transaction occurred, given that a trade is reported at the same price after several minutes. Furthermore, it is unlikely that a limit order is canceled if it is the best quote in the book.

[28] If there is more than one transaction at the limit price (here 430) in the 30-minute interval, I excluded the observation since it is unclear which of these transactions hit the order in the limit order book.

occurred at 13.10.58, and two contracts are "purchased" by the book and 158 contracts are purchased by market makers.

Table B-2 gives an example of a trade against a large sell order in the book of limit orders.

As is seen from the change in the limit order book between 11.26.38 and 11.34.39, the time of the first transaction ($P = 650$, $Q = 5$) is 11.34.39 (reporting time is 11.42.10). Then at 11.50.44 the large sell order in the book ($P = 680$, $Q = 105$) is hit. This trade is reported 4 minutes later.

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